Toward 3D-Printed Movable Tactile Pictures for Children with Visual Impairments

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ABSTRACT
Many children's books contain movable pictures with elements that can be physically opened, closed, pushed, pulled, spun, flipped, or swung. But these tangible, interactive reading experiences are inaccessible to children with visual impairments. This paper presents a set of 3D-printable models designed as building blocks for creating movable tactile pictures that can be touched, moved, and understood by children with visual impairments. Examples of these models are canvases, connectors, hinges, spinners, sliders, lifts, walls, and cutouts. They can be used to compose movable tactile pictures to convey a range of spatial concepts, such as in/out, up/down, and high/low. The design and development of these models were informed by three formative studies including 1) a survey on popular moving mechanisms in children's books and 3D-printed parts to implement them, 2) two workshops on the process creating movable tactile pictures by hand (e.g., Lego, Play-Doh), and 3) creation of wood-based prototypes and an informal testing on sighted preschoolers. Also, we propose a design language based on XML and CSS for specifying the content and structure of a movable tactile picture. Given a specification, our system can generate a 3D-printable model. We evaluate our approach by 1) transcribing six children's books, and 2) conducting six interviews on domain experts including five teachers for the visually impaired, one blind adult, two publishers at the National Braille Press, a renowned tactile artist, and a librarian.

Author Keywords
Tactile Pictures; 3D Printing; Movables; 3D Modeling;

ACM Classification Keywords
H.5.m. Information interfaces and presentation

INTRODUCTION
Movable pictures, such as those found in lift-the-flap books, are popular in children's books. They are beneficial for the development of emergent literacy in young children. These pictures are movable in that the paper on which the pictures are printed has non-stationary parts that children can move with their hands by lifting, pulling, and spinning these parts. These movements then cause the visual content of the pictures to change. For example, when the child lifts a flap, another object that was previously hidden underneath the flap appears, as shown in Figure 1. These types of tangible interactions with movable pictures are mostly paper-based with no electronics involved. Through such interactions, children are able to connect kinetic experiences (flipping) with visual experiences (something appears).

Figure 1. Current children's books with movable parts, flipping paper flap to uncover hid pictures(top), roll spinner seeing iterative hid pictures(bottom left), or slide up to trigger other parts' movement(bottom right).

For children who are visually impaired (VI), however, the benefits of movable pictures are limited. VI children can still obtain the kinetic experiences as they flip, pull, and spin. But they are unable to relate these kinetic experiences to corresponding visual experiences. They are unable to see that a flap is a part of an object or that there is another object underneath. When the visual experiences are inaccessible, the kinetic experiences offer limited benefits.

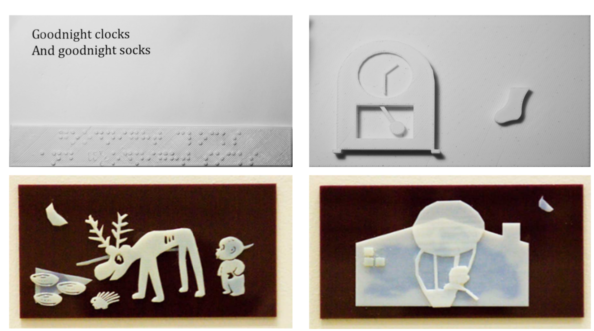

Figure 2. 3D-printed stationary tactile pictures from Goodnight Moon (top), Harold and Purple Crayon (bottom).

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3D printing has been shown to be a promising method to interpolate pictures in regular children's books accessible to VI children [13, 19]. A picture can be 3D modeled and printed to be touched, felt, and understood by a VI child. Figure 2 includes some examples of 3D-printed tactile pictures based on *Goodnight Moon* and *Harold and the Purple Crayon*, two children's book classics. However, thus far, 3D printing has been limited to static images.

Figure 3. 3D-printed *movable* tactile pictures (our work).

In this paper, we present a set of 3D structures designed as building blocks for creating *movable* tactile pictures that can be 3D printed (see Figure 3). We further present a design language for specifying the content and the structure of a movable tactile picture based on XML and CSS (analogous to Web design). We evaluate this approach first by transcribing six existing children's books and next by reporting our interviews with domain experts.

RELATED WORK

3D printing has emerged as a promising method for helping parents replicate tactile books [13]. In addition, 3D printing has been used for tactile visualization for people who are visually limited [7]. 3D printing affords ease in replicating and customizing book images, which are key challenges in creating tactile graphics [14], while helping children with visual impairments develop emergent literacy [19].

For parents interested in creating tactile graphics, there are resources and guidelines [18, 20] that introduce essential elements of good tactile pictures. For example, these guidelines emphasize the importance of interaction and mobility. The majority of tactile books have mobility features that guide children's interactions. Figure 1 shows how current tactile books incorporate mobility interactions. A bunny is moving through the book page by page, from the room to the bed, saying goodnight to everything. If tangible interaction provides nonvisual access to the pictures [6, 17], how can we incorporate interaction features into 3D-printed books?

Books that incorporate tangible interactions encouraged children's interests into the content, opening up perceptual motor skill that evolves to linguistic skills [12]. Holding children's attention is the key to develop emergent literacy in association with books [5]. Therefore, books combining various tangible techniques with 3D printing can play a huge role in promoting children's active participation [8, 16]. Because interaction engages disabled children in an inclusive learning process and encourages development of early narratives [4], tangible interaction would be an essential component of 3D-printed tactile books.

The majority of parents and teachers of VI children do not have a clear understanding of 3D printing, even though this emerging technology helps them create unique educational materials for their children [20]. Online 3D design warehouses [11, 15] have provided the easy opportunity for them to print a pre well-made 3D design. For example, it is not necessary to have a refined skillset to design a fine giraffe in 3D; even blind children can print a giraffe via voice command and then touch it to get a notion of what it looks like [21]. 3D warehouses also enable reuse of 3D tactile models for novice designers. But if parents want to customize a premade model by integrating mobility to create a tactile book, how does the technology support their needs is another area uncovered.

FORMATIVE STUDIES

Moving Primitives

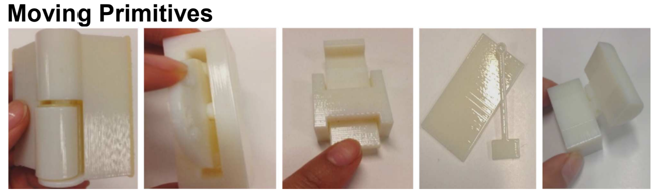

Figure 4. 3D-printed moving primitives, hinge, spinner with holder, pulley, swing, and opener (from left to right).

We undertook first formative study to understand the range and rate of paper-based moving mechanisms appear in today's children's books and to determine whether 3D-printed models can be created to emulate these moving mechanisms. We surveyed many children's books (n > 70), and focused 32 children's books that incorporate movable pictures and identified several common moving structures, such as hinge, pulley, and spinner. Mostly, out of 10 regular books for age 0-3 children who develop very early stage of literacy, 1 book had movable parts, such as lifted flap, and some really popular books were recreated as interactive books. We experimented with different methods that came up from theses books into 3D-equivalents (Figure 4).

Design Workshops

Figure 5. Two design workshops. Participants freely utilize Lego bricks, Play-doh, and other craft materials to design movable tactile pictures from children's book.

Our second formative study was designed to help us understand how individuals would approach the design of movable tactile pictures. We were particularly interested in individuals with high motivation but little or no prior experience with 3D printing. We invited local middle and high school students to participate in two design workshops (n = 6, n = 18, respectively). They came to our workshops as they were self-motivated to learn about a new technology, 3D printing. Figure 5 shows design process from workshops. They were given a task of creating a 3D model based on a movable picture in a children's book. They were free to choose their favorite books to model (more motivation). Instead of using 3D modeling software, students were given a set of physical materials since those are more accessible for novice designer (e.g., Lego bricks, Play-Doh).

Figure 6. Students' hand-made movable tactile pictures.

Overall, students maintained a high interest throughout the design activity. They created many interesting tactile models (Figure 6), such as a hot-air balloon carrying a boy (*Harold and the Purple Crayon*), a giraffe behind a door that opens (*Dear Zoo*), a butterfly with wings that bend (The Very Hungry Caterpillar) and a gorilla with rotating arms hitting its chest (*From Head to Toe*). They liked to relate familiar experiences with mobile objects, such as flapping wings and swinging doors.

Wood Prototypes

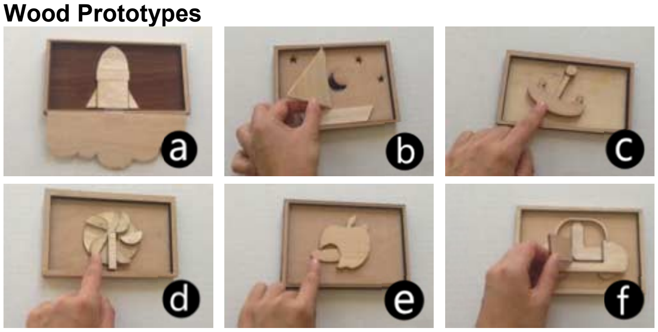

Figure 7. Wooden prototypes of movable tactile pictures. A rocket hidden by cloud (a), the moon uncovered by the waving sail (b), swinging biking (c), a spinning giant wheel with falpping carts (d), a warm passing through the apple (e), and a car with opening door and two spining wheels (f)

The aim of our third formative study was to create initial prototypes of movable tactile pictures and gather preliminary data on how young children may react to these pictures. We used wood as the material and a laser cutter as the fabrication technique to create a series of prototypes to illustrate selected scenes in children's books.

Figure 7 shows some of the prototypes. The rocket covered by a cloud (a) is an example of a hinge, as is the moon behind the sail (b) of a boat. The biking roller coaster (c) is an example of a swing, and the giant wheel is an application of a spinner (d). The spinner is easily applied to any kind of wheel, such as the tire, which is combined with another hinge for the car door, which uncovers a chair and handle inside the car (f). If the rotating angle is limited, it will be also used to represent seesaw, etc. To present a caterpillar that eats through the apple, a pulley is a trigger that enables children to move a part of picture (e).

Figure 8. A sighted child plays with a movable tactile picture, playing and interacting like handling toys

We brought our prototypes to a local preschool to observe how sighted preschoolers interacted with these movable pictures. Figure 8 shows how kid plays with tactile pictures. At this early stage of our research, sighted children were good proxies for gathering initial feedback. We were interested in (1) how much they are involved in interaction with pictures, (2) how much they intuitively interact with moving parts, and (3) how they play with moving tactile pictures. Sighted children naturally opened the door of the car, waved the sail of a boat, touched behind the flag, spun the wheel, and pushed and pulled the caterpillar. One child made his own narrative with the rocket while playing, saying, "Ready, 5, 4, 3, 2, 1, blaster!" Another asked what was behind the apple. The sighted preschoolers dealt with the tactile pictures as toys; they had a lot of curiosity, and tinkered with movable part of each picture despite the lack of context.

MOVABLE TACTILE PICTURES

The goal of this research is to enable the creation of 3D printed tactile picture books that a VI child can touch and move. Here, we present a suite of reusable 3D components we developed for the purpose of creating movable tactile pictures.

Design Goals

During our formative studies, we identified a number of design requirements that have influenced many of our design choices as we were developing these 3D components.

- **Easy to move and touch:** This design element supports the goal of the project, i.e., making tactile pictures movable and touchable for VI children.
- **Easy to print:** A model can look nice in a design environment yet not be easy to print with a low-cost 3D printer. The model may have invalid geometry. It may require support material. It may be necessary to break a model into parts that can be separately printed.

• **Easy to assemble:** When the pieces are printed separately, the process of assembling them must be easy.
• **Easy to customize:** It should be possible to customize various aspects of a component.
• **Easy to reuse:** The parts should be easy for people to reuse to make new tactile pictures.
• **Hard to break:** Young children are often *destructive*. Parts should be sufficiently sturdy to allow repeated uses.

There are additional factors worth considering but not as pressing as those above: Are models mass producible? How can we incorporate multiple materials and colors?

Page and Canvas

We modeled a book as a series of tile-like pages. Each page is composed of three types of components: canvases, tactile objects, and connectors. A canvas acts as a container for one or more tactile objects. Each tactile object is physically joined to a canvas by a connector. The most basic page has one canvas, one object, and a connector joining the two. A more complex page may have multiple canvases of different sizes and different heights, all joined together. We model a canvas as a flat, rectangular solid. The attributes are sizes and positions. A canvas can have a frame and rounded corners.

Tactile Objects

Relief

Relief is the most common form of tactile graphics apper in today's children's books for VI children. A tactile artist creates a master mold using clay or equivalent materials. Then a specialized printer is used to press paper against the mold to re/produce the image in relief. Two methods can be used to bring relief patterns into 3D. One way is through the use of a 3D scanner. Another way is to use computer vision to extract salient features and map them to different heights. Then a terrain map type of structure can be generated as shown in Figure 9.

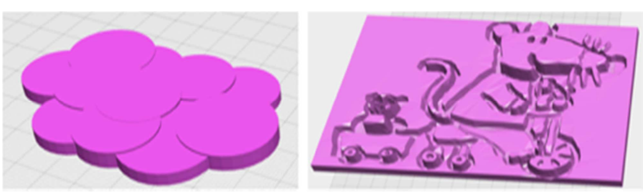

Figure 9. Relif patterns in 3D-printed tactile pictures. Additive method that brings volumes up (left), and subtractive method that line of areas put back from canvas base (right)

3D "Things"

Many premade, ready-to-print objects are now available on sharing sites such as Thingiverse. We used two methods to incorporate premade "things" into a model. The first method involves choosing a prominent side or viewing perspective, for example, the profile view of a cow or a top view of a bucket. This method is preferred when the story needs to emphasize a particular attribute of an object, for instance, how tall a cow is. Given an imported model, the process of obtaining a perspective 3D model is as follows: First, we define a plane cutting through the imported object. Next, we define a large cube on one side of the plane. Finally, we take the difference between the object and the cube to obtain a perspective representation of an object. This process results in a flat surface of 3D tactile picture to be attached flat canvas, being cutt out the part of 3D object with a sharp surface.

The second method involves representing an object as the whole, for example, the entire cow or the entire bucket. This method is preferred when the story emphasizes free exploration of an object from multiple viewing perspectives; for instance, what does a cow look like?, and how thin its legs are? at a different page. Given an imported object, we may keep it as is, scale it to convey its relative size in comparison with another object, or flatten it a bit to reduce the overall thickness of the page, as shown in Figure 10.

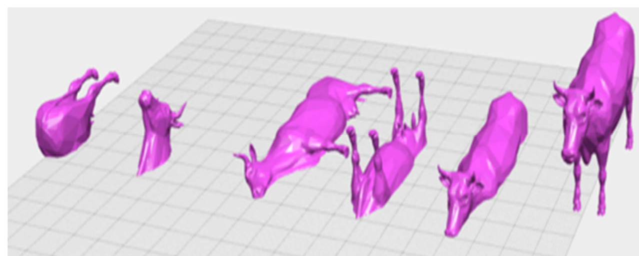

Figure 10. A pre-made cow model in various perspectives, split in half x-, y-, z-axis. So that a butt and tail, a head, side view, four legs, top view, and the entire appearance (from left to right) can be represented as series.

Movables

We defined a *movable* as a set of structure components that can be added to, or integrated with canvases and tactile objects to make them movable by a VI child.

Hinge

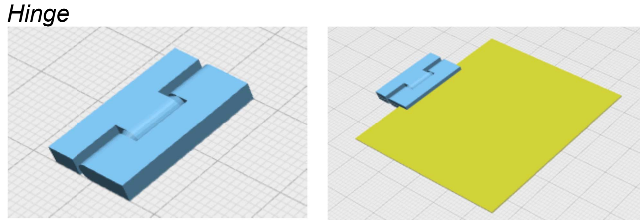

Figure 11. A hinge movable (left), added to a canvas (right).

A hinge movable is designed to provide a tangible experience equivalent to that of opening a door or flipping a lid. Many hinge models can be found on Thingiverse. We tested several and decided to settle down to one, [Thing No. :436737] because (1) it is printable without scaffolding, so even low-end printer can print, (2) it fits our canvas models quite well by combining it through as shown the right of Figure 11, (3) it does not need additional fabrication because printed at once, and (4) it is parametric so that we can customize size, length, volume of nubs, and so forth. Several attributes, such as radius and height of nubs, gap between slot and cone head are adjustable. We made enhancements to the model to make a print-and-assemble design possible. First, we added a clamp-like structure to make it easy to attach an existing tactile picture page to it. Second, we created a trough-like component that can be glued to a canvas as a holder of the hinge, when those parts were printed separately with mid-end 3D printers.

Track

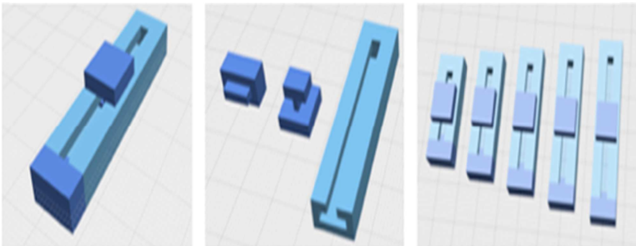

Figure 12. A track movavle (left), in parts of cover, placeholder of tactile picture, and pathholder (middle), with varying heights (right)

A track movable is designed to enable a tactile object to be moved by a VI child along the direction of the track, for instance, dragging a rocket from down side of a picture to the upper side, and towing a bumper car from the left side to the right. We model the track after a typical drapery track, which consists of a long horizontal track in an upside-down T shape, so that an arbitrary tactile object can be attached to a moving platform. (Figure 12).

Spinner

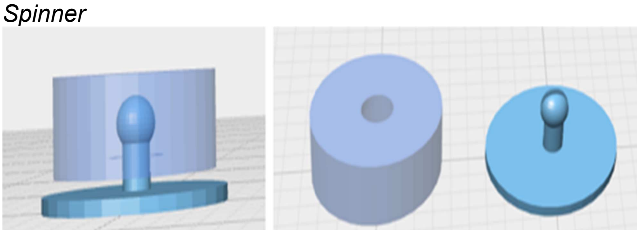

Figure 13. A spinner movable combined (left), in parts of pivot and rolling disc (right).

A spinner movable enables a tactile object to be spun, turned, or rotated by a child, for instance, turning a wheel of a vehicle. For VI children, there are plenty of physical analogies to the real world in toys such as cars and trains. We model the spinner using two components. One component is a base with a pivot. The other is a wheel with a flat top disc that connects to a tactile picture. The components can be printed separately and then put together. A rolling tactile object can be placed on top (Figure 13).

Slider

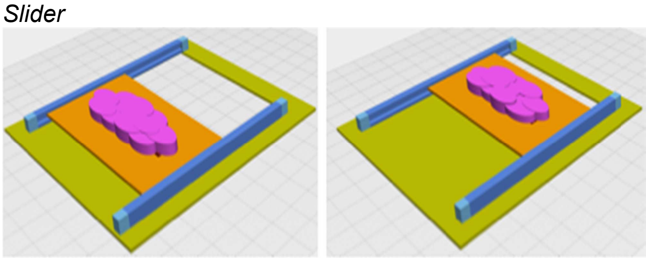

Figure 14. A slider movable carrying a cloud. A tactile cloud picture is placed on top of base that slides through side path.

A slider movable enables a child to slide a canvas to the side, for instance, to reveal the content underneath the upper canvas. In comparison, a track movable is mainly used for moving a single object. The physical analogy a child can relate to would be a French door. A slider has two tracks along the two sides parallel to the direction of movement (Figure 14).

Lift

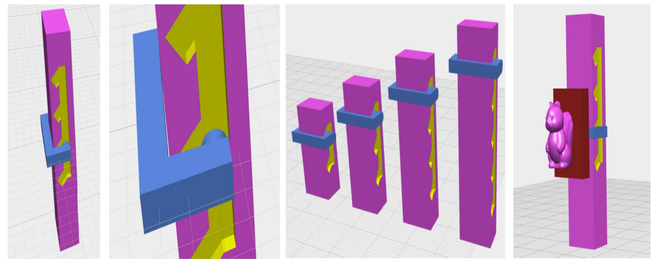

Figure 15. A lift movable to raise or lower an object. According to the the number of slots, a squirrel tactile picture is carried in different height, being combined to the holder.

A lift movable enables a child to raise or lower a tactile object. It is modeled as a vertical stack with a track on each side (Figure 15).

CONCEPTS

Our goal in terms of promoting emergent literacy for young children is to enable the creation of a new class of tactile pictures that are *movable* so that they can convey mobility concepts that would be hard to do using traditional static tactile pictures.

Linear Movement

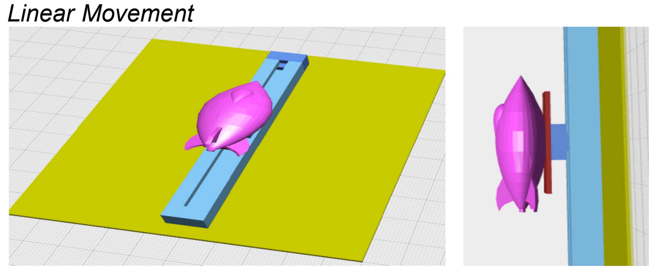

Figure 16. A rocket can be moved up and down through path.

This example conveys the concept that a rocket can move along a straight line. It is achieved using a tactile object (rocket), a canvas, and a track (Figure 16).

Further/Higher Vs. Nearer/Lower

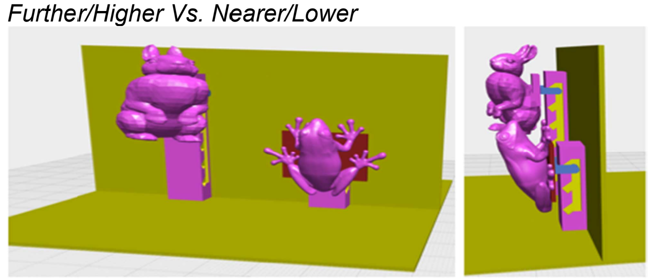

Figure 17. A rabbit can “jump” highter than a frog.

This example conveys the concept that a rabbit jumps further than a frog. A child can pull a rabbit and a frog up from the ground and discover that the rabbit can be pulled higher. It is achieved using two lift movables, each of which holds an object, at different heights (Figure 17).

Front/Behind

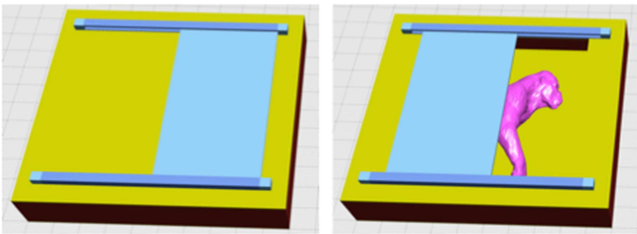

Figure 18. A gorrila is behind a sliding door.

This example conveys the concept that a gorilla is behind a door. A child can slide the door and discover the gorilla behind it. Also, a handle and window can be added upon the door to represent details, as it is another individual canvas. This effect is achieved using a slider movable, two canvases, and several tactile objects (Figure 18).

Motion

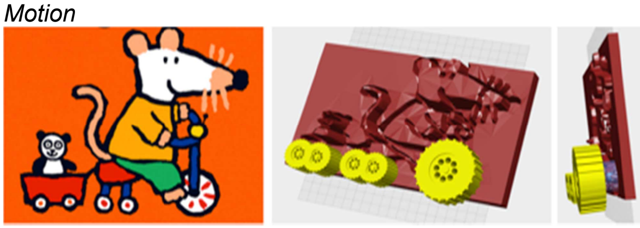

Figure 19. Wheels of a tricycle and a trailer spin.

The example conveys the concept that the wheels of a cart spin. It is achieved using multiple spinner movables, a tactile object of a wheel attached to each spinner, a raised-line model of a bicycle and a cart, imported tire-shaped 3D objects, and a canvas holding everything (Figure 19).

DESIGN LANGUAGE

Our first contribution is the design of a suite of reusable 3D printable components that can be composed into a variety of movable tactile pictures. We share our models as STL files that can be imported into the design space of a currently available 3D modeling software application. The designer can use a mouse and a keyboard to move, scale, pan, and rotate these models to form a coherent picture. However, two issues must be considered. First, the composition process is manual and laborious. Second, considerable skill is required to operate the GUI of the 3D modeling software, and serious understanding on 3D spatial recognition to perform the composition task. We argue that the task of designing a page of movable tactile pictures could be made simpler by drawing on the analogy of the task of designing Web pages. The two pillars of Web design are HTML for content/structure and CSS for style. We can take inspiration from these concepts.

We propose a design language for specifying a movable tactile picture based on XML and CSS. We chose XML since it is the most popular MarkUp language specifying “contents”, out of other programming option. Similarly, CSS was chosen due to its popularity on specifying “styles”, that can be applied to unify design on a "set" of pages. A designer can define the content and structure of a tactile picture in an XML file and can also specify the style attributes of each element in a style sheet (CSS) to uniformly apply on related files. Combined XML/CSS will reach out to the entire web development community, which is far larger than that of the 3D printing and design. Another important benefit is that XML/CSS is text-based and is accessible to blind users via a screen reader, which means even sharing task is simply copying text based code and pasting into the web browser. Note that we do not claim that XML/CSS is at a level of abstraction accessible to everyone. What we do claim is that this level of abstraction would empower a much larger user population than skilled 3D modelers to contribute to the 3D movable picture design. Moreover, our system can pave the way for others to build a WYSIWYG editor to further lower the barrier.

Hello Squirrel Example

This most basic example puts a squirrel tactile object (imported from an STL file) onto a blank canvas.

```
<canvas>
    <object src="squirrel.stl">
</canvas>
```

Complex Example

```
<canvas>
  <track length="30" direction="north" slope="20">
    <spinner>
       <object src="rocket.stl" x="10" y="10"/>
    </spinner>
  </track>
  <door orientation=south y="50%" height="50%">
    <canvas width="100%" height="100%">
       <object src="cloud.stl"/>
    </canvas>
  </door>
</canvas>
```

We present a complex example to highlight the key features of our design language. This example defines a rocket situated above a spinner, which is situated beneath a track. This rocket can be rotated and moved up and down. A door is added to cover the lower half of the canvas (y = 50%, height = 50%). A cloud is added on the door. This door can be opened along the south direction, as an equivalent of wood prototype in Figure 7a.

Implementation

To implement the functionality to generate a model from a specification, we need to redesign all our models as programs that we can invoke with different parameters. Our initial choice was OpenSCAD; however, we found a better solution in OpenJSCAD [1] not only because the former lacked the crucial features of a real programming language,

[1] http://openjscad.org

but also because it provides modeling capabilities equivalent to OpenSCAD as well as supports Javascript, allowing us to use both object-oriented and functional programming. For instance, we are able to represent each component as an object with easy to customize attributes and combined with other objects programmatically. Also, we could use existing Javascript libraries to parse the XML and style sheet in the design specification. We plan to open our source to compile the design into 3D models.

APPLICATIONS

The goal of our research was to make more children's books with movable pictures accessible to VI children. Therefore, we applied our approach to the task of transcribing regular children's books into movable pictures.

Dear Zoo

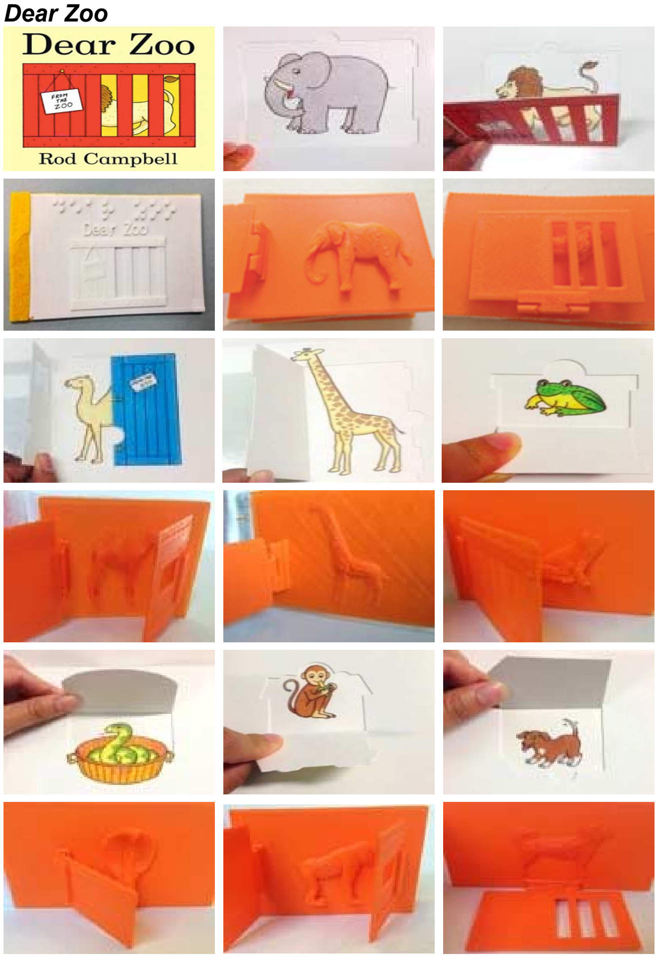

Figure 20. All pages in *Dear Zoo* with braill printed cover.

We modeled all eight pages in this book as shown in Figure 20. This book was a good test bed for our proposed design language because all the pages share a common moving mechanism (i.e., hinge) but vary in details, such as the tactile object, the orientation of the hinge (horizontal vs. vertical), coverage (half vs. full), and configuration (one side vs. split). We used the same template and customize certain aspects of this template to generate these models.

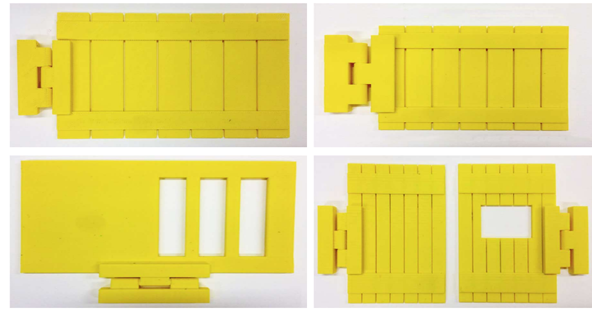

Figure 21. Doors with various tactile patterns and cutouts.

We used four different types of doors to enhance the variety in the touch experiences (Figure 21). These differences allow children to evolve from thinking about the simple shape of the door to experiencing various moving directions shapes, and unique attributes.

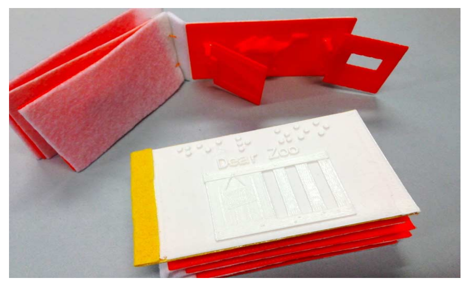

Figure 22. Dear Zoo as two volumes of binder.

Real book spine like format is still important feature to be given for *book reading* experience, so we bound pages as book format with the title printed cover page (Figure 22).

All the Fun of the Fair

Figure 23. Selected pages in *All the Fun of the Fair*. A spinning giant wheel (left), swinging biking roller coster (middle), and sliding bumper car(right).

The second book we chose was *All the Fun of the Fair* by Robert Crowther. This book employs a rich set of moving mechanisms. Figure 23 shows the three scenes using variety of movements. A rolling wheel is represented by a spinner, which is combined with the wheel frame as a tactile picture. A biking roller coaster is turned into a swing with shapes of human passengers. The horizontal track is used to represent a bumper car in a playground. Children can move the picture of a boy riding a bumper car to the left and right.

When I'm Big

Figure 24. Selected pages in *When I'm Big*. A lift lofts the rocket (top), and a slider carries a fire fighter riding an automatic ladder to reach the roof (bottom) .

The third book we transcribed was *When I'm Big* by Paula Hannigan. We chose this book because it delivers spatial concept of linear up/down very well with iterative interaction in different pages within various situations. We were interested in scenes that include elements that go up and down. We used lift movables and slider movables to achieve this effect, attaching relative tactile pictures on top (Figure 24).

Hop, Skip, and Jump, Maisy

Figure 25. Selected pages in *Hop, Skip, and Jump, Maisy*. Maisy's riding automobile(left) and bike (middle), with spinner, and drikning juice slided by track (right).

The fourth book we transcribed was *Hop, Skip, and Jump, Maisy* by Lucy Cousins. This book illustrates the daily life of Maisy mouse. It includes many kinds of interactive mobility. For example, wheels of a car and a bike are modeled using a spinner movable with a wheel object attached to it. The picture of Maisy drinking juice represents the remaining amount of juice in the glass, held upon a track movable. VI children can pull down the track through the path, touching the top of "juice" with their other hand, and feel how the relative height of the juice decreases, understanding a virtual concept they will never be able to see directly in real life (Figure 25).

What's the Opposite?

Figure 26. Selected pages in *What's the Opposite*. A rocket behind the cloud flap(left), a car behind a flag flap(middle), and a door flap opening (right).

The fifth book we transcribed was *What's the Opposite?* by Eric Hill (Figure 26). This book introduces spatial concepts in contrast, as children lift the flap and uncover something behind it: a rocket under the cloud, a moving car behind the flag, etc. Flapping parts of each page are combined with a hinge that enables readers to turn over objects.

Gossie Plays Hide and Seek

Figure 27. A page in *Gossie Plays Hide and Seek*. A tree swing is defined by spinner movable.

The sixth book we transcribed was *Gossie Plays Hide and Seek* by Olivier Dunrea. This book includes a set of examples of spinners by which children uncover hidden objects (Figure 1, bottom left). One interesting feature is that Gossie bird is getting on the swing that hangs over the tree (Figure 27). Connected with tactile pictures of tree and bird, this feature will more specifically introduce the concept of a tree swing to blind children. Our design language was able to specify the tree and the spinner movable in limited angle. The swing has to be separately modeled, printed, and added to the small flat disc top.

EVALUATION BY DOMAIN EXPERTS

We presented our prototypes to various domain experts to receive feedback and to understand the potential benefits and limitations of the prototypes from diverse perspectives. Six interviews were conducted including 10 participants. The experts participating in these interviews were 1) a blind adult with congenital blindness, 2) four teachers of preschool-age blind children, 3) two publishers who run the Children's Braille Book Club at the National Braille Press (NBP), 4) a renowned tactile graphic artist with more than 30 years of experience, 5) a teacher at a school for deaf children, and 6) a librarian who runs a children's maker space. Each interview ran for about an hour. During an interview, we demonstrated a series of 3D-printed tactile pictures and asked the expert(s) to give us feedback.

Motivator for Active Reading

Compared to stationary tactile pictures, all experts agreed that movable pieces help children learn mobility and spatial concepts by being actively engaged in the book reading. Usually, VI children are in a passive reading situation; they listen to parents and teachers reading. Giving control to children with movable pictures encourages them to dive deeply into the story. The Teacher of blind and deaf students said that having an opportunity to manipulate parts of pictures is a huge motivator. Even for sighted kids, tinkering with pictures allows them to pay attention to what they are doing and helps them retain a focus on mobility.

Literacy Evolution through Variations of Interaction

All teachers and the artist liked the four variations of doors of *Dear Zoo*, because they believed this teaches distinct concepts by same iteration. Children will learn what the cage looks like on the first page, and then concentrate on the smaller door to feel how it is different from the previous plain shape. Children finalize this development in their emergent literacy as they open a pair of doors in two directions, or a flap door down. This process presents the versatility of door shapes and opening actions. Not only that; by touching part of animal inside via the ribs of the cage and through the window, children can try to guess the salient feature of the animal, such as monkey's tail and bumps on a camel's back. This activity can be the trigger for remembering the specific animals.

Post-assembly as a Fun Activity

Our movable pictures are often broken down into separate flat pieces in order to print faster and more reliably (e.g., avoid scaffolding). Post-assembly is necessary but we were concerned about the burden it may put on users. The librarian and the teachers of VI children commented that doing special tasks makes the educational material unique for their children. They suggested the process of putting individual pieces together *"could add more fun"* to the overall reading experience and would *"make the book even more meaningful to an individual child."*

Design Considerations

From the discussions with experts, we have identified several important design considerations for further improvements to our approach in creating 3D-printed movable tactile pictures.

How should a series of concept be presented?

As the door example from *Dear Zoo* illustrates, iterating a simple interaction with various types helps children to build a firm concept of literacy. Tactile book publishers from National Braille Press recommended that we transcribe *Noah's Ark* for our next creation. That book introduces a pair of animals on each page, using different postures and perspectives. At the end of the book, a composite of all the animals reveals different perspectives, their relative size differences, and presents the spatial concept by relying on the animals' relative positions, such as in the sky where birds *fly*, and on the ground where the snake *crawls*.

What is the age of the child?

A child's developmental level of literacy depends greatly on the age of the child. For older kids who already know what a mouse looks like, the tactile picture needs to present very detailed appearance of a mouse, e.g., including four legs and a relatively fat thigh. However, for children ages 0–2, who have never heard of or touched a mouse, it is more important to emphasize its long, curvy tail and big round ears, even if exaggerated beyond those of a mouse.

What is the key intended message to convey?

The relative size of objects in one page and the simplicity of the abstraction are controversial points, so we need to be careful in considering these design factors. When the book is targeting young children and we want to introduce the shape of an animal, experts say we do not need to consider the size at that page. For example, an elephant on the first page of *Noah's Ark* can be the same size as a duck on the second page, because the two pages are intended to convey the concept of shape not relative sizes of each animal.

How should a picture be simplified?

The level of simplicity follows two previous design considerations: age and key idea. A good tactile picture highlights only one concept per object at one page. If too much detail is incorporated, it causes distraction. To keep children's attention on the picture, it needs to focus on the noticeable feature of object interpreted in a tactile picture.

How can co-reading be supported?

Sighted children hear countless other relevant words as well as a story when their parents co-read children's books, thus enhancing book-reading experiences [1, 2]. Transcribing an exact picture is an important task, but providing context by formatting the page to encourage questioning and answering will induce strong intellectual curiosity in children. For example, a window in a door at *Dear Zoo*, leads children to touch inside the window first, can foster interaction between children and parents, asking and answering to guess what that is, and building substantial bonds that help co-readers understand children's interests.

How can textures and colors be incorporated?

Most of our prototypes were uniform in color, and their textures were based on a single material. Several experts commented that high-contrast colors could be attractive to children with residual vision. They advised against precise colors, which is almost impossible for current 3D printing without painting. For example, a giraffe's body does not necessarily need to be ocher in color with brown spots. One suggestion was to use one solid color for the background, another solid color for an animal's body, and yet another color for doors in *Dear Zoo*. In addition, polygonal textures, such as raised dots, could be used to represent the brown spots on the giraffe's body without coloring them.

Other Suggestions and Comments

Experts also had a few comments on our next iteration. They suggested that the book be printed as same as original book published. Grabbing too small pieces makes the page more fragile, but larger 3D-printed objects are more legible. All of the experts recommended soft textures, e.g., using fabrics and yarn. It was commented that smoothing the surfaces would enhance the tactile experience and make it more attractive. Synthesizing several printing techniques or even hands-on fabrication of various materials will enrich children's understanding of natural attributes of real-life objects. In addition, pictures always support children's development of literacy; tactile pictures will provide children an excellent opportunity to learn braille inversely. By putting simple words in braille beside the tactile pictures and movables, VI children will remember braille efficiently with the memory of touch experience.

LIMITATION AND FUTURE WORKS

In this work, we elected to focus on domain experts who are advocates for VI children as user test subjects. It is a sensitive matter to conduct "study" on young children with visual impairments. Treating VI children as subjects in controlled experiments in this phase should be extremely cautious. We rather want them to receive quality models that have been iteratively designed and validated by domain experts. Rather, we delivered our physically printed tactile picture books to the community has VI children, such as family, school, and the public library for people with visual impairments, Colorado Talking Book Library (CTBL) for circulation. Also, we shared the printable file online, recording more than 100 downloads per books, and we have started collecting feedback from users. We will focus our research efforts into see the effectiveness of 3D printed movable tactile pictures as educational materials, by observing differences on literacy development level given regular children's books and our model. We would love to report our findings as design probe to define more moving primitives, and improve the proposed system in near future.

CONCLUSION

We present an approach to creating 3D-printed *movable* tactile pictures for making children's books' interactive contents accessible to VI children. We defined five 3D movable structures that can be used to transcribe mobility features from pictures, demonstrated how our approach could be applied to the transcription of six children's books. Findings from six interviews with domain experts revealed that movable tactile pictures would be desirable for VI children. Several ideas for improvements and refinements to our technique are highlighted.

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