Adults' and Children's Mental Models for Gestural Interactions with Interactive Spherical Displays

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ABSTRACT

Interactive spherical displays offer numerous opportunities for engagement and education in public settings. Prior work established that users' touch-gesture patterns on spherical displays differ from those on flatscreen tabletops, and speculated that these differences stem from dissimilarity in how users conceptualize interactions with these two form factors. We analyzed think-aloud data collected during a gesture elicitation study to understand adults' and children's (ages 7 to 11) conceptual models of interaction with spherical displays and compared them to conceptual models of interaction with tabletop displays from prior work. Our findings confirm that the form factor strongly influenced users' mental models of interaction with the sphere. For example, participants conceptualized that the spherical display would respond to gestures in a similar way as real-world spherical objects like physical globes. Our work contributes new understanding of how users draw upon the perceived affordances of the sphere as well as prior touchscreen experience during their interactions.

Author Keywords

Interactive spherical displays; mental models; touchscreen displays; touchscreen gestures; children; adults.

CSS Concepts

• **Human-centered computing ~ Human computer interaction (HCI) ~ Interaction devices ~Touch screens**

INTRODUCTION

As the adoption of spherical displays continues in public settings (e.g., museums and science centers) for both educational and entertainment purposes [12,13], there is a need for research to inform the design of future interactive applications for these displays. Although interaction design for touch-interactive spherical displays was first studied in human-computer interaction research in 2008 [9], spherical displays that support multi-touch gesture interactivity have only recently become commercially available (Figure 1) [32]. For example, in 2019, NASA's Space Communication and Navigation center publicly deployed a touch-enabled spherical display to help the general public learn about space exploration [33].

Figure 1: Children and an adult interacting with a touchscreen spherical display, courtesy Pufferfish, Ltd.

When designing for new form factors, it is vital to consider what factors will influence users' interaction preferences. Norman [18] notes that users form their own **mental models** when interacting with an interface: *"In interacting with the environment, with others, and with the artifacts of technology, people form internal, mental models of themselves and of the things with which they are interacting [p.7]."*, and that these mental models are what guide users' interactions with an interface. So far, gestural interaction methods proposed for spherical displays have mainly been designer-driven [9,13,25,26], rather than informed by users' own mental models. However, prior work has shown that designer-defined gestures are often more conceptually complex than gestures defined by end-users [14]. This is because designers' mental models are usually based on abstract mappings, in contrast to end-users' mental models, which are based on analogies of interacting with the physical world and prior experience [14].

Previously, we [22] established that users' touch-gesture patterns on spherical displays differ from those on flatscreen tabletops, and speculated that these differences stem from dissimilarity in users' mental models of interaction with these two form factors. One possible reason that users' mental models would vary could be because spherical

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displays, which present digital content continuously around a borderless surface, are metaphorically different than flatscreen tabletop displays, which present a rectangular viewport into a digital world [8,22]. This metaphorical difference could have led users to think about interacting with spherical displays in a different way than interacting with flatscreen tabletop displays. Other possible reasons include differences in users' perceptions of affordances or experience with these two form factors. Legacy bias [15] strongly influences users' touchscreen behaviors on flatscreen tabletop displays, and it was not clear how much this would transfer to spherical displays. We believe that, to understand the design of intuitive interactions for spherical displays, it is necessary to construct a deeper understanding of how adults and children conceptualize their interactions with this technology, and how these mental models differ from mental models for interacting with tabletop displays. It is vital to study both children and adults, because results from prior work on designing touchscreen interactions for adults do not always generalize to children [4,19], who have different cognitive abilities and motor skills.

To help us understand how form factor might influence the ways children and adults conceptualize gestural interactions with a spherical display, we used a think-aloud dataset collected from a user study we conducted previously [22], which adapted the *user-defined gestures* method (also known as a gesture elicitation study), from Wobbrock et al. [31]. For this study, we focused on children aged 7 to 11 because this is the age range typically targeted by public learning exhibits [3]. The gesture elicitation method is one way to help designers understand users' preferences for gestural interactions with an interactive system. During the study, the participants proposed gestures for task prompts on the sphere while thinking aloud about their gesture creation process. In our previous paper [22], we reported *physical characteristics* (e.g., hand pose) of user-defined gestures on spherical displays. In this paper, we report a thematic analysis of users' think-aloud utterances from the same study. Though using data from the same study, the novel contribution of this paper is that we seek to understand the underlying *mental models* that drive users' interactions with spherical displays.

Our findings confirm that the spherical display form factor strongly influences users' mental models of interaction. For example, participants conceptualized that the spherical display would respond to gestures in a similar way as real-world spherical objects, like physical globes respond to physical manipulations. This work contributes the following to the SIGCHI research community: (1) novel insights into children's and adults' mental models for interacting with spherical displays and how these mental models differ from gestural interaction mental models for flatscreen tabletops; (2) characterization of differences in how children and adults conceptualize their interactions with touch-enabled spherical displays; and (3) implications for designing interactions and surface recognition technology for spherical displays. Our goal here is to present gestural interaction mental models for spherical displays; future work should be conducted to validate these mental models with follow-up studies and propose a user-defined gesture set that complies with both children's and adults' mental models. Our work contributes new understanding of users' mental models for interacting with spherical displays and will inform the research and design of future applications for spherical displays.

RELATED WORK

We situate our study within three research areas relevant to interactive spherical displays: (1) user-defined gestures methodology; (2) gestural interactions for flatscreen displays; and (3) gestural interactions for spherical displays.

User-Defined Gestures Methodology

Introduced by Wobbrock et al. [31], the *user-defined gestures* methodology is a participatory design approach that involves eliciting gestures from users to design touchscreen interactions. This method was originally based on the *guessability* technique [30], in which users are shown a visual effect of a system command (also known as a *referent*) and are prompted to propose gestures they think are suitable for causing that effect. The users are also asked to expose their gestural interaction mental model by verbalizing their thought process while proposing a gesture. These elicited mental models can then be thematically analyzed to gain a deeper insight into users' gesture creation process. Prior work has established that designers and developers often come up with gestures that are conceptually complex and less discoverable to users since experts do not always have the same gestural interaction mental models as end-users [14]. Gestural interaction mental models play an important role in how users interact with touch-based interfaces [18]. In many cases, end-users' perception of gestural interaction are based on the interactive system's affordances as well as users' prior experiences [1,18]. These experiences may include any previously used touch-interactive technology or interaction with physical objects like hand-held controllers. Our study [22] used the gesture elicitation approach to elicit gestural interaction mental models from children and adults. This methodology enabled us to systematically look into users' thought processes while they proposed gestures for application-agnostic touchscreen tasks used in prior work on spherical and flatscreen tabletop displays [19,23,24,26,31].

Designing Gestural Interactions for Flatscreen Displays

Several studies have used the gesture elicitation study approach to gain a deeper understanding of end-users' gesture preferences for both small and large flatscreen displays, such as multi-touch tabletop platforms [5,14,19,29,31]. Wobbrock et al. [31] conducted a gesture elicitation study with non-technical adults to design interactions for multi-touch tabletop displays. Based on their analysis of users' think-aloud utterances, the authors discussed several gestural interaction mental models for flatscreen tabletops including use of reversible gestures and influence of common desktop paradigms. Rust et al. [19] conducted a gesture elicitation study with both children and adults to understand children's gestural interaction preferences for flatscreen tabletop displays. The authors found that both children and adults manifested "legacy bias" by proposing gestures based on their prior touchscreen experience. Multiple studies have also found that the orientation of the display affects users' gestural interaction mental models [5,29]. To investigate adult users' gestural interaction preferences for vertical wall displays, Wittorf and Jakobsen [29] used a gesture elicitation study approach. They found that users were more likely to prefer using gestures resembling physical manipulation of real-world objects while interacting with vertical wall displays as opposed to flatscreen tabletops. In another study, Anthony et al. [5] examined gestural interaction for horizontal tabletop and vertical wall displays and found that due to different ergonomic affordances between the two form-factors, users attempted gestures using multiple fingers on vertical touch walls more frequently as compared to horizontal tabletops. The findings from the aforementioned studies indicate that the physical and ergonomic affordances of touchscreen platforms may affect users' mental models and the gestures that users find intuitive and natural in a specific context.

While previous work has provided insight into designing user-defined gestural interactions for flatscreen displays, these gestural interactions may not generalize to spherical displays. Findings from prior work [5,29] show that the characteristics of the gestures people attempt varies for different touch screen platforms. Thus, we analyzed think-aloud data we collected during a gesture elicitation study [22] to understand children's and adults' gestural interaction mental models for spherical displays, and to compare these mental models to prior work on flatscreen tabletop displays [5,19,29,31]. Our work will inform the design of future interactive applications for spherical displays that draw on the perceived affordances of spherical interfaces and expectations of users of all ages.

Designing Gestural Interactions for Spherical Displays

Much of the existing prior research in human-computer interaction on designing gestures for interactive spherical displays has taken a designer-based approach (i.e., gestures designed by experts, not users) [7–10,25–27]. The first interactive spherical display was developed by Benko et al. [9], in 2008. Benko et al. [9] also proposed a set of designer-defined touchscreen interactions, such as scaling and dragging interface objects, as well as interactions to enable collaboration around the sphere, such as flicking and send-to-the-opposite side. These interaction methods allowed users standing on one side of the display to collaborate with another user standing on the opposite side of the display. In a lab-based study, Bolton et al. [10] developed and evaluated multiple software-based "peeking" techniques that allowed adult users to view opposite parts of the sphere. Recently, with commercial availability of multi-touch spherical displays [32], researchers have started to move out of the laboratory context to provide recommendations for designing interactions with spherical displays based on *in-the-wild* studies. Williamson et al. [26] conducted an in-the-wild study with interactive spherical displays to investigate the impact of supporting different types of interaction styles on user dwell times at the sphere. The authors found that providing more interaction styles encouraged users to explore more features, thereby increasing dwell time. Soni et al. [21] performed an in-the-wild observational study with groups of children and adults and found that users were sometimes uncertain about the interaction possibilities with the spherical display and did not find interaction with the spherical form factor to be very natural or intuitive. Most of the interface prototypes tested in the above studies used gestures designed by experts rather than informed by users' mental models.

An important first step towards understanding user-defined gestures for interactive spherical displays was a laboratory study we conducted [22]. The analysis we reported [22] compared *physical characteristics* (e.g., hand pose, number of fingers) of children's and adults' gestures on interactive spherical displays to flatscreen displays and found differences in users' gesture preferences. For example, users were more inclined to use multi-finger or whole-handed gestures on the sphere as compared to flatscreen tabletop displays. In that paper [22], we speculated that users were conceptually thinking about spherical displays in a different way than they think about flatscreen tabletop displays. In this paper, we analyze think-aloud data from the same study [22] to examine what differences may exist in children's and adults' gestural interaction *mental models* for spherical and flatscreen tabletop displays. In this paper, we go beyond prior work by explicitly highlighting the mental model patterns users draw upon while interacting with spherical displays and examining the extent to which this thought process is different or similar to the gestural interaction mental models reported in prior work on tabletop displays. Based on our findings, we discuss implications for surface gesture recognition technology and user interface design for interactive spherical display applications that are natural and intuitive for users of all ages.

METHODOLOGY FOR ELICITING MENTAL MODELS

We adapted the *user-defined gestures* approach [31], to elicit users' mental models for interactions with spherical displays. For completeness we outline the study methodology here, but for full details, see Soni et al. [22]. The main goal of this paper is to analyze users' think-aloud utterances to understand their mental models for interaction with a spherical display, and compare these to prior work on mental models for flatscreen tabletop interaction.

Participants

As described in Soni et al. [22], a total of 33 participants (20 children and 13 adults) participated in our study. Out of 20 children, the first five were pilot participants to help us improve our study protocol. In addition, two children decided not to complete their participation in the study. Thus, data from 13 children (5F, 8M) aged 7 to 11 (M: 9.20, SD: 1.44) and 13 adults (9F, 4M) aged 19 to 52 (M: 31.58, SD:

10.03), were used for our final thematic analysis of users' think-aloud responses. To ensure that our sample was representative of wide audiences at public learning spaces, we recruited our participants by distributing flyers at a local museum, school, and a public library, and also via email lists. All the study sessions took place in a private room at our university or a public library. After the study, all participants completed a questionnaire about their prior experience with touchscreen interfaces. Consistent with findings from national surveys [35,36], the majority of our participants considered themselves "average" or "expert" with respect to their general touchscreen familiarity. All participants were compensated for their time with $10 and three small prizes.

Think-Aloud Pilot Sessions with Children

To enable a deeper understanding of adults' and children's gestural interaction mental models for spherical displays, our goal was to elicit high-quality think-aloud responses from both of our user groups. As children sometimes have difficulty following the think-aloud process [2], we ran pilot sessions with five children to ensure that we could effectively help children understand the think-aloud process. The results of our pilots showed that children had trouble exposing what they were thinking while proposing gestures. Children were more likely to talk about what gestures they were doing on the sphere (e.g., "I am tapping now"), rather than talking about how they came up with the gesture they proposed. To ensure elicitation of rich qualitative data, we introduced a think-aloud practice session for all participants in which we practiced performing a two-column addition problem. The think-aloud practice session occurred before participants began interacting with the sphere. Conducting these think-aloud practice sessions allowed us to aid children in learning how to use the think-aloud protocol, thereby helping children verbalize their gesture creation process more fully during the study.

Study Tasks

We used the gesture elicitation study approach by asking participants to propose gestures for 17 commands (including one practice command) on the sphere, as described in Soni et al. [22]. Table 1 shows all 17 commands with corresponding experimenter prompts. Some of these commands are sphere-specific, which only apply on the spherical form factor (e.g., reset sphere rotation), whereas others are common touchscreen commands (e.g., undo). These commands were selected based on prior work on spherical and flatscreen displays [19,23,24,26,31]. During all the gesture elicitation tasks, we prompted participants to use the think-aloud process in order to gain insights into the mental models they were formulating while interacting with the spherical display. This enabled us to compare users' mental models for interaction with spherical displays to what has been found by prior work on flatscreen tabletop displays.

Procedure

During our study, participants proposed gestures and explained their gesture creation process for the 17 commands. We used the *production technique* [14] to avoid legacy bias and asked participants to perform three gestures (two one-handed and one two-handed) for each command, while explaining their gesture creation process for each of them. Upon proposing three gestures for a command, participants rated their gestures for *goodness* and *ease* [31]. The order commands were presented to the participants was counterbalanced, as described in Soni et al. [22].

Commands	Experimenter Prompts
Bigger (practice)	Pretend you are making an object or window bigger.
Turn sphere in X (s)	Pretend that you are turning the sphere side to side as you see on the sphere.
Turn sphere in Y (s)	Pretend that you are turning the sphere up and down as you see on the sphere.
Smaller (t)	Pretend you are making an object or window smaller.
Flick (s)	Imagine another person is also interacting with the sphere and pretend you are flicking an object in a direction towards that person to share the object with them. They will have to catch the object.
Stop rotation (s)	Pretend that you want to stop the sphere while it is rotating.
Move an object (t)	Pretend you are moving an object to a new location.
Send to the other side (s)	Imagine another person is standing on the other side of the sphere and pretend you want to send an object to that person. The object will stop in front of them.
Next (t)	Pretend you want to view the next object in a sequence.
Reset sphere rotation (s)	Imagine you have tilted the sphere and now you want to reset the sphere to the way it was before.
Undo (t)	Pretend that you need to undo the most recent action you took.
Copy (t)	Pretend you are creating a copy of an item on the sphere.
Remove (t)	Pretend you are permanently deleting an item on the sphere.
Pick one (t)	Pretend that you are picking one object.
Pick many (t)	Pretend you are picking many objects.
Local rotation in X (s)	Pretend that you are rotating an object side to side as you see on the sphere.
Local rotation in Y (s)	Pretend that you are rotating an object up and down as you see on the sphere.

Table 1: Commands and prompts used in our study [22]. (s) denotes sphere-specific commands and (t) denotes traditional touchscreen commands.

We obtained informed consent from all adult participants and the parents of the child participants prior to starting the session. Children were additionally given the option to assent to participating in the study of their own volition. After consenting, all participants did a practice think-aloud activity. Participants then interacted with a fireworks application for five minutes to reduce any novelty effect of the spherical display [19]. Then, we walked participants through the study process using a practice task including explaining the gesture rating questions. After the practice task, participants were asked to propose gestures for the 16 remaining commands on the sphere while using the think-aloud protocol. For each command, participants were first read a prompt describing the command (Table 1), and then saw a video showing the visual effect of the command on the sphere, similar to Wobbrock et al. [31]. Participants were asked to propose a gesture they thought was most suitable to make that effect happen on the sphere, while verbalizing their thought process. At the end, participants completed a demographics questionnaire. Children completed the questionnaire with the help of a researcher. Our protocol was approved by our Institutional Review Board.

Apparatus

The study was conducted using a 24-inch diameter commercially available interactive spherical display, called PufferSphere 600M (34 ppi) [32]. The height of the spherical display was 1475 mm (58 in). The PufferSphere utilized interior cameras to capture touches. As described in Soni et al. [22], a C# application was used to present the visual effects of the command to users. Video was recorded over both shoulders of the participants during all study sessions.

Data Analysis

Our research team transcribed the think-aloud utterances from the study sessions. We analyzed a total of 1238 think-aloud utterances (622 from adults, 616 from children), corresponding to 1238 gestures (out of a total of 1248 gestures) proposed by our participants. We discarded think-aloud data corresponding to 10 gestures (8 gestures by children and 2 gestures by adults) since participants were not able to come up with a gesture for those commands. We analyzed these transcriptions using inductive thematic analysis, based on the Braun & Clarke approach [11]. Inductive thematic analysis is a bottom-up approach used to systematically organize large-scale qualitative data into themes based on their natural relationships, without fitting the data into a pre-existing coding scheme [11]. To start the analysis, three researchers individually read an independent set of the users' think-aloud utterances (30% or 35% of the sample, each) to become familiar with the data. Then, these three researchers plus a fourth independent researcher came together as a group to review all the think-aloud utterances and iteratively grouped relevant utterances together to capture the emergent themes over the course of several meetings. During our iteration, we identified some themes that collapsed into each other while other themes were broken down into individual themes. This process helped us ensure that the think-aloud data within a theme bound together meaningfully, with a clear distinction between multiple themes. A think-aloud utterance was included under multiple themes if the utterance had multiple ideas about users' mental models for interaction with the sphere. For example, this utterance from a child participant while proposing a gesture for the stop rotation command: "*Kind of like stopping something from spinning like a ball or anything and it slows down because of friction.*" [child, stop rotation] was considered under two themes: **applying physics principles** (*"...slows down because of friction."*) and **visual similarities with real-world spherical objects** (*"spinning like a ball"*). In the end, we came up with eight main themes apparent in children's and adults' mental models for interaction with spherical displays.

FINDINGS: GESTURAL INTERACTION MENTAL MODELS

Our goal is to understand what unique mental models users formed during their interaction with the spherical display and to what extent their mental models are similar to what has been identified in prior work on flatscreen tabletops. In our analysis, we identified eight major themes related to users' gestural interaction mental models for spherical displays. We discuss each theme and how it is supported by our data. We present these themes divided into three-subsections, namely: (a) what mental models are **similar** between spherical and flatscreen tabletop displays, (b) what mental models are **unique** to spherical displays, and (c) what mental models are similar or different between **children and adults**.

What Mental Models are Similar between Spherical Displays and Flatscreen Tabletop Displays?

In this section, we discuss themes we saw for spherical displays in relation to similar prior work on flatscreen tabletop displays by Wobbrock et al. [31].

M1: Influence of Windows and Touchscreen Paradigms

For flatscreen tabletops, Wobbrock et al. [31] found that participants often thought about WIMP-style interactions [34] based on their prior experience with desktops, e.g., closing an application by imagining a widget located at the tabletop screen's top-right corner [31]. Similarly, for spherical displays, children and adults thought about interaction modes based on their prior experience with current technology. Participants imagined windows-based paradigms such as an X button to remove: *"like clicking the X button on a computer to delete."* [child, remove]. A new development in our study is that participants also thought about their prior experience with more recent mobile touchscreen interaction paradigms while interacting with the sphere. For example, an adult participant referenced conceptualizing both a backspace key and a swipe-to-undo gesture when designing a gesture to undo an action on the sphere: "*like a backspace or an undo, swiping off to the left makes whatever I just did go away.*" [adult, undo].

Unlike previous findings for tabletop displays, for spherical displays we saw participants thinking about digital and physical controls based on their prior experiences, particularly when performing directional gestures around the sphere. For example, participants imagined a digital control panel to help them rotate an object on the sphere: *"imagining there is a control panel on the side and move [fingers] on that [control] indicating that I want the object to move in that direction ..."* [adult, local rotation in y]. Another participant imagined a physical control such as a joystick when trying to flick an object in a particular direction around the sphere: *"...I came up with [the control] because it's like remote controlling a vehicle, it's like a joystick you move the circle up or diagonal or that way."* [child, flicking]. In addition to these examples, the following quotes show that participants were consciously using their prior experience with touchscreen and desktop computers: *"I am already biased using computers…"* [adult, next] and *"...swiping to the next picture as if I am using an iPad."* [adult, next]. Our findings show participants draw on multiple types of prior technology experiences, and more often reference digital and physical controls, when interacting with spherical displays.

M2: Axes of Gesture Motion for Dichotomous Tasks

Wobbrock et al. [31] noted that users often conceptualized using reversible gestures for dichotomous tasks (e.g., bigger and smaller) on tabletops. Reversible gestures are those in which performing a gesture in the opposite direction produces the opposite effect [31]. The most common type of reversible gestures users conceptualized in prior work on tabletops were linear in nature (e.g., right/left, up/down, or diagonal swipes), that is, gestures along the rectangular tabletop's length, width, and diagonal dimensions [31]. Our study with spherical displays also included dichotomous tasks. However, in contrast to Wobbrock et al.'s [31] flatscreen findings, our participants sometimes conceptualized using circular gestures for dichotomous tasks while interacting with the sphere, in which participants moved their hand in more than one spatial direction, such as in the clockwise and counterclockwise directions. For example, a child participant rotated all five fingers of the left hand over an object in the clockwise direction to make the object smaller, and suggested rotating counterclockwise to make the object bigger: *"because you are spinning it or making it smaller, you could also use it the other way to make it bigger…. It is like turning it, but you are not going to end up turning it, so it feels like the squishing one..."* [child, smaller]. This finding indicates that, in the users' conceptual model, an interactive spherical display should be able to recognize and differentiate between clockwise and counterclockwise gestures for dichotomous tasks.

M3: Going Beyond the Interactive Area on the Sphere

Some users in Wobbrock et al.'s [31] study conceptualized interacting with an area beyond the rectangular edges of the flatscreen tabletop's interactive screen for some tasks. Similarly, in our study with spherical displays, both children and adults thought about interactions that go beyond the interactive area on the sphere. For example, an adult participant imagined flicking an object off the sphere towards another device nearby: *"I will flick it away as if I am flicking it off the screen on other devices."* [adult, flicking]. This observation of participants thinking about off-screen space for spherical displays is surprising because, unlike tabletops where the edges of a flatscreen display can be thought of as a viewport into the digital world, spherical displays are continuous and borderless, where an interaction area beyond the screen usually does not exist [8]. Instead, any interface object panned far enough along in one direction will eventually travel all the way around the spherical display [8]. For spherical displays, participants also conceptualized interacting with an area of the sphere that is outside their field of view. For example, some participants considered the area of the sphere that is not in their field of view as a repository to bring in objects: *"like you could [spin] another picture and get it, you can have a picture from here and bring it here."* [child, next]. The above finding signals that, in users' mental models, the sphere should be able to recognize cues in users' gestures that signal their intentions to interact with the world beyond the circumference of the spherical display.

M4: Acting Above the Spherical Display

In addition to these off-screen interactions in the same plane, prior work [31] saw that participants also sometimes gestured *above* the flatscreen tabletop display, even though the authors explicitly instructed participants to touch the table while gesturing. Similarly, for spherical displays, we saw that both children and adults sometimes gestured above the sphere's interactive surface. One child participant performed a pinch gesture in the air using all five fingers of her right hand to copy an object and then placed all five fingers on the screen to paste the object back: *" ...picking up a copy, picking up a paper and putting it down."* [child, copy]. In another instance, a child participant hovered his hand above an object on the sphere as if he were holding a baseball and rotated his hand to rotate the object: *" ...if in real life you took a baseball and twisted with your hand, the dots would move in a circle on the globe…"* [child, local rotation in y]. This finding indicates that, similar to flatscreen tabletops, participants sometimes conceptualized interacting with spherical displays using above-the-surface gestures.

What Mental Models are Unique to Spherical Displays?

In addition to the above themes which were previously identified by Wobbrock et al. [31] for tabletop displays, we also saw new themes that emerged.

M5: Applying Physics Principles

A frequent theme apparent throughout our analysis was the way participants discussed physics principles such as speed, momentum, friction, and force while interacting with the sphere. More specifically, this type of discussion was often seen when participants proposed gestures for commands that involved making an interface element travel a large distance across the sphere or manipulating the whole sphere at once. Participants talked about their mental models of how the speed of their gesture should influence the rotation speed of the whole sphere: *"I will swipe slowly against [the direction of rotation] to decelerate it."* [adult, stop rotation], and: *"you can put your hand on it and slowly slow it down and eventually stop it, slowly breeze it in the opposite direction."* [child, stop rotation]. Participants conceptualized that the number of fingers or hands they use would determine the sphere's rotation speed: *"it's kind of like the other one I did but with more fingers, more fingers mean stop faster"* [child, stop rotation]. Participants also mentioned how gesturing with one finger felt weak on the sphere: *"trying to think what would give it momentum, one finger feels weak…"* [adult, flicking]. We saw participants thinking that using both hands would provide strength to the gesture: *" ...if I put a little more strength into the gesture by using two hands, there is* *more movement involved."* [adult, turn sphere in y]. In addition to the above findings, participants also mentioned the concept of friction while gesturing: "*maybe spinning backward a little, it is based on kind of how friction works...*" [child, stop rotation]. Overall, we saw participants thinking about different principles of physics while interacting with spherical displays, which was not reported previously in the same way for flatscreen displays.

M6: Visual Similarities with Real-World Spherical Objects

During our study, we saw that children's and adults' gestural interactions with spherical displays were heavily influenced by the visual similarity between the spherical display and real-world spherical objects around them. Some viewed their interaction as if they were interacting with a real-world three-dimensional object, such as a physical ball: *"trying to make it move like a 3D ball, trying to communicate that I want to see the bottom since the sphere can't move."* [adult, turn sphere in y], and: *"just like basketball ... you just cup your hand around and throw."* [child, flicking]. In addition, some participants also compared the sphere to a physical globe during their interaction: "*it would be like if a globe was spinning, you could stop it like that.*" [child, stop rotation], and: "*now I am using multiple fingers and swiping it all the way across, just imagining almost like spinning a globe around."* [adult, send to the other side]. Overall, we saw that the physical form factor of the display caused users to view the sphere as a real-world spherical object and influenced their mental models with respect to what interactions they thought could be possible on the sphere.

M7: Local Reference Frame

In contrast to flatscreen tabletop displays, where multiple users share the same perspective, spherical displays are omnidirectional and provide each user with a different perspective depending on their position around the sphere [8]. While system designers of spherical displays implement the interactions from a global coordinate reference frame [8,9], in our study we saw that both children and adults thought of gestural interactions with the sphere from their local reference frame or viewpoint. Participants in our study often described their interactions with the sphere in their local coordinate system such as moving right, left, or backward with respect to their body position around the sphere. "*I would swipe up and to the left...*" [adult, local rotation in x]. One participant imagined tapping on the top left quadrant of the sphere to undo an action: *"We think from windows computing environment, we can have [a] back button, we can tap on the left top quadrant of the sphere."* [adult, undo]. In addition, we saw that participants imagined the placement of the UI elements on the sphere with respect to their local reference frame, such as: *"...I am trying to drag it down into the trash can."* [child, remove]. This finding indicates that irrespective of the omnidirectional nature of the sphere, users conceptualized gesturing and placement of the interactive UI elements around the sphere in the context of their local reference frame, based on the viewpoint they had as they stood in front of a certain part of the sphere.

M8: Mental Models for Collaborative Gestures

During our study, we asked participants to propose gestures for two collaborative tasks (e.g., flicking (to another person) and send-to-the-other-side [9]) that enable users to collaborate with another person standing on the opposite side of the sphere. We observed that, in addition to suggesting gestures in the XY plane, participants often imagined a third dimension that cut through the middle of the sphere when proposing gestures for collaborative tasks. Both children and adults conceived the sphere as possessing and supporting interaction in three dimensions to let them send an object across the sphere: "*I will push it to the other side."* [child, send to the other side], and: *"the system would recognize that I'm trying to tunnel it through."* [adult, send to the other side]. Participants also conceptualized that applying hand pressure would affect an interface object's depth: *"...I could just push it back, just even a finger, two fingers, I could push it back and kind of pressing for some reason on the center of the image now and where I could just affect its depth by pushing it a certain level of pressure."* [adult, send to the other side]. We also saw participants imagining interaction with digital controls to accomplish collaborative tasks that require large directional movements across the sphere instead of employing touchscreen gestures*: "I am selecting the image using two fingers and then instead of making large movement I am imagining cardinal points near the image to select where you want the image to go."* [adult, send to the other side]. This reliance on controls might be due to users' preference for precisely controlling an object's travel direction while sending an object across the sphere. Overall, for collaborative tasks, participants imagined interaction modes that let them send an object across the sphere quickly with directional control.

Differences between Children's and Adults' Gestural Interaction Mental Models?

During our thematic analysis, we observed some differences between children's and adults' mental models.

Perceptions of Collaboration Around the Spherical Display

We observed differences between children and adults in the way they verbalized their perceptions about collaborating around the sphere. We saw adults expressing concerns while performing collaborative tasks about how their gestures might impact others interacting around the spherical display: "*it's the same gesture but different direction, and the reason I think less of an intuitive match is because there could be people standing on any other side—...of the sphere..."* [adult, send to the other side]. This might be because adults were concerned about violating social protocols by reaching into other users' interaction areas [20]. However, children did not express such concerns and often conceptualized playing physical games with other users on the sphere when talking about collaborative tasks. For example, children talked about tossing something back and forth like a physical ball on the sphere: *"like you are pushing it, I was thinking that it would work, it is like tossing something back and forth*." [child, flicking], and: *"like throwing a ball onto the other person,*

Mental Model Themes	Main Takeaway	
Influence of Windows and Touchscreen Paradigms (M1)	Participants consciously used previously acquired experience with touchscreen and desktop computers while interacting with the spherical display.	✓
Axes of Gesture Motion for Dichotomous Tasks (M2)	Participants expected the sphere to identify and differentiate between clockwise and anticlockwise circular gestures.	✗
Going Beyond the Interactive Area on the Sphere (M3)	Participants expected the sphere to recognize cues in their gestures that signal intention to interact with the world beyond the circumference of the spherical display.	✓
Acting Above the Spherical Display (M4)	Participants conceptualized using in-the-air gestures just above the surface while interacting with the spherical display.	✓
Applying Physics Principles (M5)	Participants consciously used different principles of physics while interacting with the spherical display.	✗
Visual Similarities with Real-World Spherical Objects (M6)	Participants capitalized upon their prior experience with interacting with real-world spherical objects during their interaction with the spherical display.	✗
Local Reference Frame (M7)	Participants conceptualized gesturing and placement of interactive UI elements around the sphere in the context of their local reference frame.	✗
Mental Models for Collaborative Gestures (M8)	Participants imagined interaction modes that let them send an object across and through the sphere quickly with directional control for collaborative tasks.	✗

Table 2: Summary of gestural interaction mental models for spherical displays. Rows with the ✓ and ✗ symbols signify similarity or difference in users' mental models for spherical displays as opposed to tabletop displays, respectively [31].

then they throw it back." [child, send to the other side]. Overall, we saw that children and adults conceptualized collaborative interactions around the sphere differently, in ways reflective of their interests and experiences.

Frequency Analysis

We also conducted a frequency analysis of some of the think-aloud utterances to understand differences by user age. Based on our experience with the participants during the study sessions and our familiarity with the data, we identified three mental model themes that we thought might differ most by user age: (M1) use of prior experience with technology, (M5) use of physics principles, and (M6) use of real-world spherical (physical) objects. These mental model themes roughly corresponded to gesture characteristics we had already coded for our previous paper [22] when considering the Wobbrock et al. [31] gesture taxonomy, but which were only analyzed for this paper. During that coding pass [22], each utterance was coded as "yes" or "no" to reflect whether the mental model theme was present or not. Then, the same pair of one child and one adult participant was coded by four researchers, and a group discussion for each code led to refinement of the code definitions to help all the researchers reach consensus. Finally, each of these four researchers independently coded think-aloud utterances from six or seven participants. For this paper, we computed the overall frequency of "yes" codes within the child and adult groups for each theme.

Based on the frequency analysis, we found some differences in children's and adults' mental models for interaction with spherical displays. We observed that discussing physics principles while gesturing on the sphere was more common among adults (87 out of 622 utterances, 14%) than children (37 out of 616 utterances, 6%). On the other hand, children (211 out of 616, 34%) were more likely than adults (145 out of 622, 23%) to think about real-world physical objects during their interaction. Our analysis also revealed that adults (171 out of 622, 28%) were more likely than children (111 out of 616, 18%) to draw on their prior experience with current technology. Children's inclination to conceptualize interactions based on real-world objects around them can be attributed in part to how they apply and build upon knowledge from what they see and do in their real life (e.g., playing with a physical ball) to new experiences [6].

DISCUSSION

The main aim of our analysis was to understand adults' and children's conceptual models of interaction with spherical displays and compare to what has previously been found for flatscreen tabletops (summarized in Table 2). Our findings confirmed that there are differences in how adults and children conceptualize their interactions with these two form factors, and we provide specific examples of how these differences manifest in their mental models. In this section, we discuss implications of our results for designing gestures and surface recognition technology for spherical displays.

Implications for Designing Gestural Interactions for Spherical Displays

Several gestural design implications for spherical displays emerge based on our mental model themes:

Capitalize upon both physical and perceived affordances of the spherical display. Prior work on examining gestural interactions for flatscreen tabletops and vertical touch wall displays by Anthony et al. [5] and for flatscreen tabletops by Rust et al. [19] found that both children and adults showed a strong dependency on prior touchscreen experience during their interactions with these displays. In contrast, when conceptualizing interactions with spherical displays, participants' dependency upon their prior touchscreen experience was not as strong. In our study, users manifested some legacy bias by conceptualizing interactions based on their prior touchscreen experiences (**M1**); however, at the same time, we also saw participants' mental models for interaction with the sphere moving beyond legacy-inspired gestures. This is likely at least partially due to employing the *production technique* [15], which was intentionally designed to encourage participants to think beyond legacy bias.

Participants also used the physical form factor of the sphere as a cue to conceptualize their interactions with the display (**M6**). Both Wobbrock et al. [31] in their study on flatscreen tabletops and Wittrof and Jakobsen [29] in their work on vertical wall displays, observed a high prevalence of physical gestures, in which users conceptualized interacting with real-world objects on *top* of the interface. In contrast, for spherical displays, we saw users treating the sphere itself like a physical object with interactive properties beyond the digital screen it provided. Our findings reveal that users' tendency to draw upon the physical affordances of the form factor is more prevalent for spherical displays than flatscreen displays. Our participants conceptualized that the sphere would respond to gestures in a similar way as real-world spherical objects. According to Norman [16], the term *affordance* refers to the property of an interface that cues how it should be used and is described by both physical and perceived properties [16]. The affordance of a spherical display is both its spherical form factor (its physical property) as well as the perceived affordance as to how the sphere should be used (its perceived property). Based on the sphere's physical affordance, we saw that both children and adults often perceived their interactions with the sphere in a similar way as they would physically interact with real-world spherical objects like a ball or a globe. Therefore, in addition to supporting users' dependence upon their prior touchscreen experience, we recommend that designers should capitalize upon both physical and perceived affordances of the spherical display to design intuitive and natural interactions.

Provide support for circular reversible gestures. Prior work on flatscreen displays found that participants preferred using reversible gestures for dichotomous tasks, e.g., pulling fingers apart or bringing them close to enlarge or shrink an interface object [31]. This preference has also been observed in other elicitation studies, e.g., for designing interactions with flat TV screens [24]. We confirm that users will use reversible gestures for interactive spherical displays as well. However, our findings indicate some differences in the way users conceptualized reversible gestures on spherical displays as opposed to flatscreen tabletop displays. For tabletop displays, most reversible gestures were conceptualized by users in linear directions (e.g., gesturing inwards and outwards along the tabletop's length, width, or diagonal). In contrast, for spherical displays, we saw users thinking about circular dichotomous gestures where the direction of the circle signifies users' intentions behind their interactions (**M2**). This behavior of thinking about circular reversible gestures on the sphere seems likely due to the three-dimensional nature of the sphere or inspired by the ways in which users interact with real-world spherical objects. Therefore, in addition to supporting linear reversible gestures, we recommend interface designers to also support circular reversible gestures when designing touch-based spherical display applications, because users are likely to attempt these gestures on the sphere.

Implications for Surface Recognition Technology

The ways in which users conceptualize their interactions with spherical displays also has implications in informing the design of surface gesture recognition technology.

Explore in-the-air interactions for spherical displays. For spherical displays, the users conceptualized interacting using above-the-surface gestures, and formed mental models of extended interactive spaces beyond the sphere's interactive area, e.g., dragging an object off-screen to delete it or flicking an object towards another device **(M4)**. Similar observations were reported by Wobbrock et al. [31] for flatscreen tabletop displays. Based on this finding, we suggest that future work should explore designing interactions that are not confined to a user's field of view or interactive area around the sphere. Interactive spherical displays might benefit from technology to detect gestures that are performed in-the-air around the sphere, rather than just on-screen gestures.

Use a physics engine for interactive spherical displays. In our study, we saw that participants often discussed a variety of physics principles such as speed, momentum, friction, and force while conceptualizing their interactions with spherical displays (**M5**). Specifically, this type of behavior was more prevalent when participants proposed gestures for commands that involved making an interface element travel a large distance across the sphere or manipulating the whole sphere at once (e.g., reset sphere rotation). This behavior of thinking about multiple physics concepts was not prevalent in prior work on tabletops [31], possibly because those commands were typically object-centric tasks (e.g., copy) rather than world-centric tasks that involved manipulation of the entire interface (e.g., turn sphere in x). Participants in our study also used multi-finger or whole-handed gestures because they conceptualized one-finger gestures as being "weak" and thought that using a whole hand while gesturing would add strength to their gesture (**M5**). This finding resonates with and extends our prior paper [22], which highlighted users' preferences for using multi-finger or whole-handed gestures on multi-touch spherical displays. Our findings reveal users' mental models behind this behavior to help inform design.

Thus, based on our findings demonstrating users' mental models of using principles of physics while interacting with the spherical display, a physics engine [28] could be employed to give pseudo-physicality to the sphere. Using a physics engine enables consideration of concepts like friction, speed, momentum, and force, which are reflective of real-world dynamics, when designing gesture recognition technology for spherical displays. For example, gesture recognizers for multi-touch spherical displays would benefit from using time- and speed-based gesture recognition. However, given that users also attempted standard touchscreen gestures on the sphere, using a combination of a physics engine along with a traditional gesture recognizer would be the best approach for spherical displays.

Implications for Spherical User Interfaces

Norman noted that gestural interfaces are not "natural" since a purely gesture-based system makes it challenging to determine the set of interaction possibilities [17]. During our study, we saw instances in which users thought that using gestures was not always the most intuitive way of interaction. For example, we observed a mixture of user preferences for performing directional movements on the sphere. Some users preferred using natural touch-based gestural interactions to send an object across the sphere in a particular direction. Other users preferred using a digital control such as a cardinal point to help them make precise directional movements on the sphere. We need to design GUIs to scaffold and carefully guide natural user interactions [17]. Since spherical displays are still novel for general audiences, it is important to design user interfaces that conform to users' mental models or try to shift their mental models by providing more scaffolding [17,18]. We suggest that instead of absolutely removing directional control widgets, designers can gradually move towards natural interactions. Interface designers for spherical displays can employ a hybrid solution of using both control-based and natural gestures for directional movements. This design choice will foster adoption of these novel interfaces. We also call for future work to determine graphical user interface design best practices for large spherical displays.

Awareness of Technology Limitations

During our gesture elicitation study, we saw that the participants' knowledge of hardware-based limits of the touchscreen technology influenced the ways they conceptualized interactions with spherical displays. For example, one child participant mentioned that the camera might take longer to see the gesture he/she was proposing: "*I think the camera would see it better if you just swiped, the camera inside takes more time to swipe it across.*" [child, send to the other side]. As another example, an adult participant talked about the sphere responding to a gesture based on how it is programmed: *"tap and swirl, you're going to play with it until you figure out how it works so it depends on how it's programmed, came up with it from games."* [adult, send to the other side]. These concerns mentioned by our participants demonstrate their tech savviness and might have affected users' mental models for interaction. To our knowledge, none of the gesture elicitation studies in prior work have yet commented on how users' knowledge about current capabilities of touchscreen technology might influence their gestures or mental models. We speculate that this limited attention on the influence of technological constraints implies that this behavior was not seen or seen much less frequently in prior work. During our study, we saw this behavior in multiple study sessions for both adults and children. Since users of all ages now have more interaction experience with different types of touchscreen technologies in homes, classrooms, and even public spaces [4,5,33], users are perhaps now more likely to perceive technological constraints based on issues they might have come across in the past. Therefore, it is important for future work to consider the degree to which users' knowledge about current tech capabilities and limitations might influence their gestural interaction mental models.

LIMITATIONS AND FUTURE WORK

Our findings highlight how the form factor of the spherical display influences users' mental models for interaction. Since users in Wobbrock et al.'s [31] study with flatscreen tabletops had comparatively less prior touchscreen experience as opposed to users in our study, this experience might be relevant to understanding differences in mental models for interactions across these two form factors. All of our participants had some prior touchscreen experience, which, though representative of current U.S. populations [35,36], also limits the generalizability of our findings. In future work, users could be recruited from other populations and/or geographical areas outside of the U.S. that may have less current access to touchscreen devices, to investigate how their mental models for interaction with spherical displays differ from those found in our study. Also, the spherical display used in our study was large, with 24'' diameter. Different sphere sizes could also impact the way users conceptualize interactions. This paper reports children's and adults' gestural interaction mental models for spherical displays and compares those to mental models for flatscreen tabletop displays from prior work [31]. For future work, we plan to use the findings from our study to recommend a user-defined gesture set for spherical displays that draws on the expectations of users of all ages.

CONCLUSION

We report analysis of think-aloud data we collected in a previous gesture elicitation study [22] with 26 children and adults interacting with a spherical display. We identified eight themes based on users' think-aloud utterances during their interactions with the spherical display and compared these themes to what has been identified in prior work with tabletop displays. We found that the physical affordances of the spherical form factor strongly influence the way both children and adults conceptualize interactions. We present new recommendations for designing interactions from both a hardware and software perspective for spherical displays that are aligned with users' mental models.

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