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Research paper

Examining children's design processes, perspective-taking, and collaboration when using VR head-mounted displays

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ABSTRACT

We explore how children leverage virtual reality (VR) to reshape their design sensibilities and to expand their perspective-taking, which may lead to the children showing more empathic concerns for future users of their designs. We worked with middle school children, ages 13 to 14, who collaboratively designed sandbox maze models using our VR SandScape system, a spatial augmented reality (SAR) physical sandbox hybridized with a VR head-mounted display (HMD) that allowed them to experience the sandbox mazes in a full scale virtual environment. We compared this group with a second group of middle school children who worked in the same SAR sandbox without access to virtual immersion from the VR HMD. We found that the virtual immersion and multiple perspectives afforded by the HMD influenced the children's design analysis methods by motivating them to evaluate their maze models from a designer's view, a user's view, or sometimes both views simultaneously, which involved consideration of allocentric perspectives (i.e., seeing their design from others' perspectives compared to from only egocentric perspectives). The VR HMD group empathized with future users of their maze designs and approached design as an iterative problem-solving process, continually discovering and addressing new user needs. They gradually incorporated more user-accessible features such as wider paths and gentler slopes. In contrast, the Non-HMD group was less concerned about users' needs but designed more playful and creative mazes. Overall, they were more quickly satisfied with their early designs without feeling the need to iterate. We discuss the role of virtual immersion in supporting children's perspective-taking, which influences their critical or complimentary attitudes towards their design processes and design outcomes.

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1. Introduction

With a rapidly growing market of commercially available virtual reality (VR) systems (e.g., Oculus Rift (2020), Vive (2020), and Google Cardboard (2020) with its low cost attractive for use in classrooms), VR developers and designers are beginning to consider children as potential VR users. Using its immersive first-person perspective, children can leverage VR to experience simulated worlds that stretch beyond the constraints of their everyday realities (e.g., traveling to the moon or to an underwater world as a different character). Beyond its entertainment value, VR also presents unique learning opportunities because VR can expose children to multiple perspectives different from their own. This ability is especially important for children as they learn to collaborate with others and negotiate meanings by considering alternate perspectives. In particular, VR can create opportunities for children to engage in empathic **allocentric** perspectives ("world seen from another's perspective") in contrast to **egocentric** perspectives ("world seen from my perspective") (Fig. 1), which is an important experience for children learning to become designers of spaces others will participate in. While VR has already been considered a potentially powerful tool for children in educational contexts, such as learning geometry (Price, Yiannoutsou, & Vezzoli, 2020), geography (Woods, Reed, Hsi, Woods, & Woods, 2016), and even prosocial behaviors (Bailey & Bailenson, 2017), we believe VR can contribute to children's development towards becoming designers who consider multiple perspectives including future-user experience throughout their designing and making processes.

This work examines middle school-aged children, ages 13 to 14, collaboratively designing maze models with sand using our VR SandScape system, a hybrid VR and spatial augmented reality (SAR) sandbox that we developed for this study specifically. We asked pairs of children to design a maze model in a sandbox that could be built at full scale. We chose this task because it requires considering the maze from a visual perspective (e.g., How does

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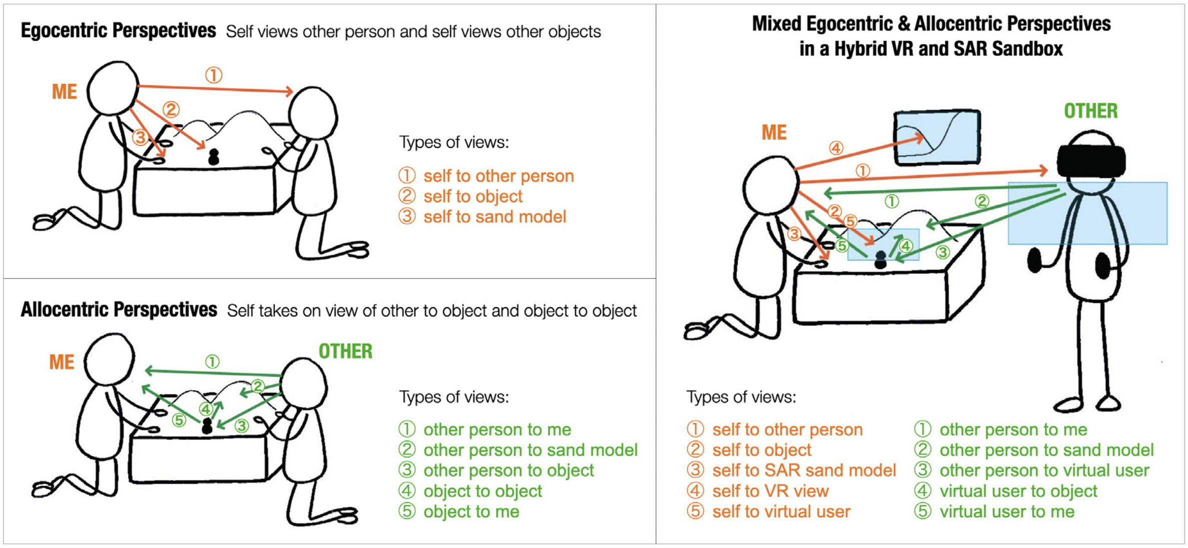


Fig. 1. Differences between **egocentric** and **allocentric** perspectives when working in a sandbox. In a hybrid VR and SAR collaboration setting, these perspectives become even more complex as perspectives from a virtual user to objects or persons are added.

the maze look from different visual perspectives and scale?) as well as a user's perspective (e.g., Is it interesting for the user to go through? Can a user successfully navigate and complete the maze?). As the children modeled the landscape, the system scanned the topography of the sandbox in real-time and rendered an explorable, full scale 3D virtual environment. Half of the pairs had access to a VR HMD with which they could immersively explore the virtual maze they designed at full scale (VR HMD group, Fig. 2 left), and the other half had a set of hand controllers and a 2D non-immersive monitor to navigate their virtual maze (Non-HMD group, Fig. 2 right). Over multiple sessions, we found that the children in the first (VR HMD) group leveraged multiple perspectives (virtual and physical) to design more accessible pathways such as wider paths and gentler slopes to help users navigate their maze more easily. As the VR HMD children alternated roles between exploring in VR and working at the sandbox, they experienced their design from multiple scales/views and noticed opportunities for improvement, made iterative changes, and approached their collaborative design using a problem-solving process similar to one professional designers use. As a result, they tended to be constructively critical and less satisfied with their early designs, expressing a desire to continue iterating. In contrast, the Non-HMD children did not focus on accessibility, did not feel the need to iterate to accommodate future users, and were more playful and liberal with their design as they were seemingly unconstrained by usability considerations. In our effort to unravel the interconnectedness of such ways of *seeing* and *designing*, the questions that guided this research are the following:

1. How do children engage with and navigate different lenses (i.e., different scales and roles of designer and user) throughout their design processes?
2. What are the affordances of shifting perspectives from an egocentric view ("world seen from my perspective") vs. an allocentric view ("world seen from another's perspective") in design, and how does it affect the design outcomes?
3. How do asymmetric (i.e., working at different stations) vs. symmetric (i.e., working at the same station) workflows affect children's perspective-taking and design?

We contribute our observation of the impact of children leveraging virtual immersion in a collaborative design setting as an enabling technology for perspective-taking and discuss potential implications for children's design processes and outcomes.

2. Background

VR in the context of learning has been explored by researchers since the early 1990s as a way to enhance spatial knowledge (Winn, 1993), facilitate experiential learning (Youngblut, 1998), or improve the transfer of knowledge and skills to the real world (Pellas, Kazanidis, Konstantinou, & Georgiou, 2017). It allows for multiple types of perspective-taking.

First, VR provides affordance for perspective-taking through what users can see visually. In VR, users are fully immersed in virtual environments that do not follow the same physics laws as the real world does. Despite VR being a new and unfamiliar environment, immersion helps users understand the mechanics of that space. In particular, environments that "change" the user's physical size help them learn about size and scale by manipulating their own size, objects, or environments in both micro and macro worlds (Gutiérrez et al., 2007). For example, through virtually observing planetary phenomena at a macro scale, students can better understand the relative size of the Earth to the sun (Bakas & Mikropoulos, 2003). Virtual environments can also present interactive models from a smaller scale, and as a result, better help students visualize microworlds (e.g., a molecule's structure) (Limniou, Roberts, & Papadopoulos, 2008). This requires children to use a lens that is unfamiliar to them, and the immersion of VR helps them be attentive to details that otherwise go unnoticed or are not well comprehended. These skills are valuable in the field of design because design sometimes requires understanding an experience that is unfamiliar to the designer. These related studies of VR and scale suggest that VR may help bridge such a comprehension gap in designing for different scales.

VR also provides affordance for perspective-taking that focuses on feelings. Recent work suggests that VR can be a driver of empathy through the embodiment of multiple perspectives (e.g., taking on a different age, gender, or ethnicity in a simulated world), challenging stereotypes and bias (Maister, Slater, Sanchez-Vives, & Tsakiris, 2015). The ability to coordinate multiple different perspectives and confront one's own perceptual bias from another's perspective (allocentric view) seems to contribute not only to learning content but to cognitive and moral development as well (Schwarz & Baker, 2017), and the "blurring of the distinction between self and other" seems to trigger empathic concerns (Proulx, Todorov, Aiken, & de Sousa, 2016). We believe

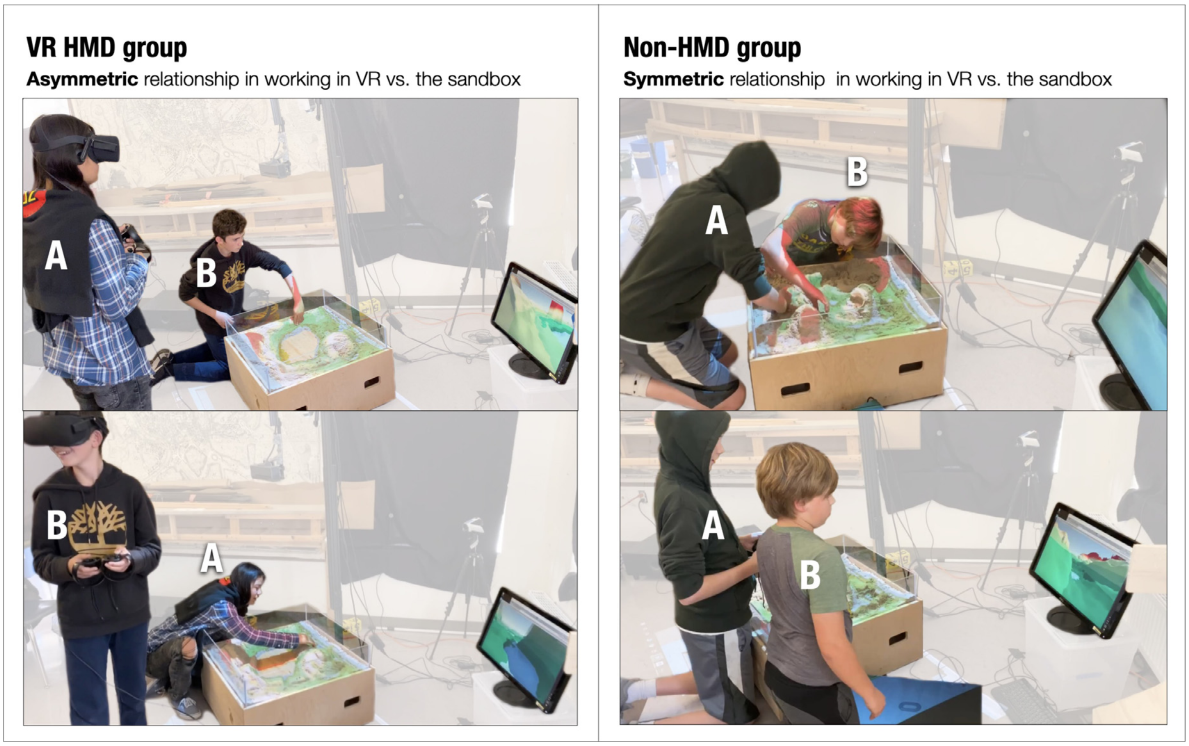


Fig. 2. The children in the VR HMD group took turns wearing the HMD and working at the SAR sandbox (taking on **asymmetric** roles). In the Non-HMD group, neither children wore an HMD and worked together from the same perspective (taking on **symmetric** roles).

VR has the potential to encourage children to use empathy in design because it provides this ability to move between perspectives and consider allocentric views. Empathy is one of the key drivers in any design process (e.g., Battarbee & Howard, 2015; Bennett & Rosner, 2019; Wright & McCarthy, 2008) as designers strive to go beyond their personal perspective, understand potential users' needs, and design accommodating solutions. HCI has a long history of studying children as designers, co-designers (e.g., Druin, 2002; Iversen, Smith, & Dindler, 2017; Kim, Bj rling, Bhatia, & Li, 2019; Yip et al., 2017) and, more recently, "inclusive designers" who actively engage in perspective-taking and design with empathy for their users (e.g., Cullen & Metatla, 2019; Garzotto & Gonella, 2011; Metatla, Read, & Horton, 2020). While VR has been explored in the context of design (e.g., in architecture (Özgen, Afacan, & Sürer, 2019), urban planning (Nan et al., 2014), ergonomics (Li et al., 2017)), such explorations have been limited to adults. There are very few studies of young children as VR users in educational or collaboration settings (with the exception of Price et al.'s study (Price et al., 2020) with children aged 8–9 years old in England), with even a limited number of studies with teens (with the exception of Kim et al. (2019)). Furthermore, existing research has not explored how VR might encourage this type of empathic perspective-taking that is beneficial for design processes. Therefore, our goals in developing VR SandScape were to:

- Enable children to experience their design from others' perspectives (allocentric views) and at different visual scales. This consideration led us to incorporate the use of a virtual environment accessed by a VR HMD and a maze task that would require using an unfamiliar scale.
- Build on children's ability to jointly negotiate the meaning and utility of different views with their partners. These ideas led us to create a collaborative setting and study their collective experience.
- Empower children to act as both designers and users of their design. This goal led us to consider a hybrid VR/SAR SandScape setting, which offers a fluid way to build, test, and then change their design based on their observations.

With these goals in mind, we developed our VR SandScape system to study how children engage in a collaborative design process using a VR HMD and an augmented physical design medium.

3. VR SandScape: System overview

VR SandScape is a hybrid spatial augmented reality (SAR) sandbox and VR system that we developed to support children's collaborative design processes from multiple perspectives. Using a depth-sensing camera installed above the sandbox, our system scans the surface of the sand in real-time and generates a corresponding three-dimensional VR rendering of the sandbox topology that is constantly changing as the children physically sculpt the "sandscape." In the corresponding VR world, the other child wearing an HMD can virtually walk through the mountains, valleys, etc., which were physically created in the sandbox, with a first-person point of view and at full scale. The physical sandbox is augmented with color projections from above to visually emphasize the sand's topographical contours such as lakes, peaks, etc. (Fig. 3c). The virtual model uses the same colors as the projection. Finally, we provide a large external monitor (going forward called "LCD") that displays the virtual user's view.

We have designed our system as a hybrid SAR & VR system for multiple reasons. First, it is not trivial for children (or adults, for that matter) to design and build a virtual world using commonly used 3D modeling software as there is a high barrier of technical prowess. Our system allows young children to quickly build a virtual environment of their own using sand, a much more familiar medium. While sand may be a more difficult material to manipulate as precisely as other materials (e.g., modeling clay),

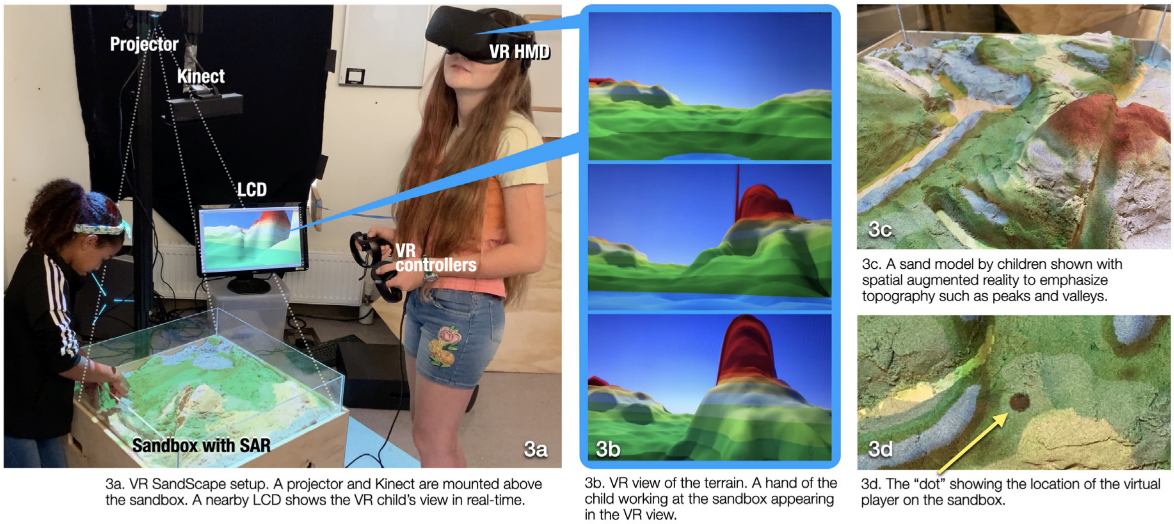


Fig. 3. VR SandScape System Overview.

its loose-grain material quality encourages both quick and playful engagement. The sandbox also encourages more collaboration than a standard keyboard and mouse, as it invites multiple hands and bodies to work in the same space together. Second, our system allows children to experience their design from different scales: a VR HMD enables the designers to immerse themselves in the virtual model at different scales, either from a birds-eye view (1:43) or from within the sand maze model (1:1). For example, a small scoop of sand at the sandbox may look like a gaping canyon in VR. Third, in VR SandScape, children can take on different roles, being the designer as well as the user of their own design. This combination of SAR sandbox and VR HMD allows children to physically design a model with the augmented sandbox and immediately check how the model looks from inside using the VR HMD. We explored the system's influence on the children's design processes and outcomes.

3.1. VR SandScape: Technical implementation

Our custom-made sandbox is 40 × 40 × 8 inches filled with Kinetic Sand (2020), which does not dry out with exposure to air and maintains its consistency. We use a Microsoft Kinect (2014) mounted 55 inches above the sandbox as the input sensor to receive depth image data from the physical sand terrain. We use Unity to poll for the Kinect depth data every frame; this data is used to re-create the terrain as a virtual object in the Unity Scene using a world space shader to render the terrain with gradient colors based on the height of the terrain. We access this environment using an Oculus Rift as our VR HMD. During each polling cycle, a delta height value is calculated between the current frame and the last. This height change is visually depicted only when the value exceeds a fine-tuned threshold to reduce the sensitivity to minor height changes and make the environment more stable instead of changing colors constantly for users when walking around the virtual terrain with the Oculus HMD. The shader employs 14 colored textures representing an elevation color map, topographic contour lines, and simulated water. The same color scheme is also overlaid onto the physical sandbox using a projector, thus visually linking the physical and virtual environments through corresponding colors. The system does not distinguish between the presence of human hands and sand terrain, so when the designer's hand is present within the sandbox, the hand becomes a dynamically moving part of the terrain in VR (Fig. 3b). For example, the sand modeler's hands can scoop up the VR user as well as change the location of the user virtually by creating moving "hand mountains." Finally, we built a first-person character in Unity with the ability to move, jump, and navigate in the virtual terrain in a 1:1 scale by binding it with Oculus OVRInput. The location of the VR user within the landscape is shown to the sandbox modeler as a moving "dot" projected onto the sandbox (Fig. 3d). Lastly, a nearby large LCD monitor shows a 2D representation of the first-person view in VR in real-time (Fig. 3a).

3.2. Related work

Augmented sandboxes have been developed since the early 2000s as an archetype for Tangible User Interfaces (Ishii & Ullmer, 1997). *SandScape* (Ishii et al., 2004) overlaid computer simulations such as contours, shadows, and drainage on top of changing sand models in real-time to support landscape architects collaboratively working on their early designs. A decade later, museums began showcasing *Augmented Reality Sandboxes* (e.g., Lawrence Hall of Science (2015)) and experimental classroom settings invited students to use these augmented sandboxes to learn about topographic maps and surficial processes in introductory geology labs (e.g., Woods et al. (2016)). More recently, a few projects have introduced VR to augmented sandboxes. For example, *Inner Garden* (Roo, Gervais, Frey, & Hachet, 2017) is a system with a SAR sandbox where a user wears an Electroencephalography (EEG) sensor that measures brain activity and represents it as animations projected onto the sand. A user could then be teleported to the same virtual terrain via VR. The system was designed for a single user to support their mindfulness exercises such as breathing, body awareness and to provide a peaceful, soothing vantage point, rather than to act as a creative design medium. *VR-Box* (Fröhlich, Alexandrovsky, Stabbert, Döring, & Malaka, 2018) is a related system designed for a game designer to build a virtual world by physically touching sand in a sandbox to sculpt the world. VRBox uses multiple Kinect depth sensors to enable hand tracking and mid-air gestures over the sandbox. The sandbox itself was not spatially augmented with animations as it was designed for a game designer who works alone wearing VR goggles and thus would not see the sandbox. These works explore platforms where users can easily create original VR environments by touching and molding sand, simplifying the design and creation of VR environments. The design of our VR SandScape builds on these prior works in that it takes advantage of our familiarity with sand as a flexible medium to support the creative process. Our work is unique, however, because we examine specifically the real-time collaborative design processes between multiple young designers with different vantage points afforded by virtual immersion, and how these diverse spatial perspectives accessed by the designers are negotiated and influence their design processes and outcomes.

4. Methods

4.1. Study design

To study how access to a VR view influences how children consider multiple perspectives in their design (i.e., seeing their designs as designers vs. seeing the designs as users), we compared pairs of children who worked with our VR SandScape system with an Oculus Rift as our VR HMD ("VR HMD group") to pairs who worked with almost the same setup but without the HMD ("Non-HMD group"). Though both groups had access to the LCD, which showed a 2D first-person view of the digital world controlled via a set of handheld Oculus controllers, only the group with the VR HMD had a way to immersively explore the virtual environment at full scale. For the Non-HMD group, the VR view's orientation was controlled by rotating a black box that concealed the Oculus HMD (Fig. 2, bottom right image) and the children could navigate the maze using the Oculus controller. We set up our system in the corner of a classroom with privacy curtains separating the study area and the rest of the classroom. The two groups did not see each other during the sessions, so they were unaware of the other group's setup.

4.2. Participants

It is important to note the age restrictions that come with current commercially available high-quality VR HMDs such as Oculus and HTC Vive: they are rated for users 13 years or older because HMDs are designed to be worn on adult-sized heads. While the HMDs come with adjustable straps, the display may appear blurry if the headset does not fit well. While brief exposure (e.g., under 20 min) to some blurriness should not be harmful (Bailey & Bailenson, 2017), effects from long-term usage are currently unknown. For safety reasons, and in adherence to manufacturer's guidelines, our study did not allow children under the age of 13 to participate in the HMD experience.

Sixteen children, seven girls and nine boys, at an urban middle school volunteered to participate in our study with their parents' permission from October 2019 to January 2020. All sixteen children knew each other as classmates. We formed eight pairs of design collaborators. Four pairs were placed randomly into the HMD group and the other four into the non-HMD group.

While twelve of them were 13 years or older, four were age 12 at the time of recruitment and turned 13 during our study. We first distributed these four 12-year-old children between two groups to have equal age distribution. We then ensured that the two 12-year-old children in the VR HMD group waited until they turned 13 to use the HMD. The two 12-year-old children in the non-HMD group did not have access to an HMD. The rest of the children were paired based on their schedule availability and remained with the same partner throughout the project. While half of the children had a brief prior exposure to VR HMD (e.g., trying out a demo at a mall), none of the children had extensive experience using VR. The names used in this paper are pseudonyms.

4.3. Design tasks

All eight pairs of children (total of 16 children) participated in three 15–30 min design sessions during their middle school electives period, with each session spaced about one week apart. All eight pairs of children were asked to use the VR SandScape system to design a maze model out of sand that could be "built at full scale at their school for them and their schoolmates to experience." We requested all children in both groups to design a "maze" (as opposed to an open-ended landscape) because a maze is an object easily understood by children of this age (13–14 years). The objective of the maze was to create a navigable environment with a clear beginning and end, as well as certain elements such as dead-end and turns along the way, which afforded interesting design decisions for the children in our study.

Each of the three design sessions had different challenges that increased in complexity to keep the task interesting over multiple sessions. Both groups received the same design tasks:

- For the first session, we asked the children to build a maze with at least one mountain and a 90-degree turn.
- For the second session, we asked the children to build a new maze with two mountains where one was twice as tall as the other one.
- For the third session, we asked the children to build a new maze that includes "a cliff that is safe but thrilling" as well as three mountains where mountain A is three times taller than mountain C, and mountain B is two times taller than mountain C, and mountain C can be any size.

In both groups, we explained the very basics of how the VR SandScape worked, i.e., the system tracks the physical sandscape and creates a virtual representation in real-time. In the VR HMD group, we explained that the virtual model could be accessed using the Oculus headset and the controller. In the Non-HMD group, we explained that the virtual model could be accessed using the LCD and the Oculus controller. For both groups, we showed how to use the Oculus controllers to navigate their virtual model, such as move forward vs. backwards, walk vs. jump, and change orientation. Both groups were told that the "dot" on the sandbox shows the location of the virtual view. We were careful not to use the term "user" nor "future user" while explaining the system to the children in both groups. Beyond explaining the basic system (e.g., how to use the controller, what the colors and the "dot" represent on the sandbox), we did not instruct the students on how to begin (e.g., which student starts at which station or that they must both be doing the same thing) and no further instructions were given. Each session was intentionally open-ended so that the researchers could study the children's organically derived participation and design processes and how they differed between the VR HMD and Non-VR HMD groups. The researchers did not interrupt the children's design process once the session was started and they could stop at any time or continue as long as they wanted until the end of their class period. Thus, the session lengths ranged from 9.5 min to 25 min, with an average length of 15.34 min. At the end of each session, we asked all the children to fill out a 2-question survey and verbally answer a few questions about their experience.

4.4. Data analysis

Data from our study include video recordings of the children's design activities, images of their maze designs, interviews about their activity, responses to the post-session questionnaire, and field notes. We transcribed the video data of the children talking to themselves and their partner during the design sessions with accompanying descriptions of what the children were doing

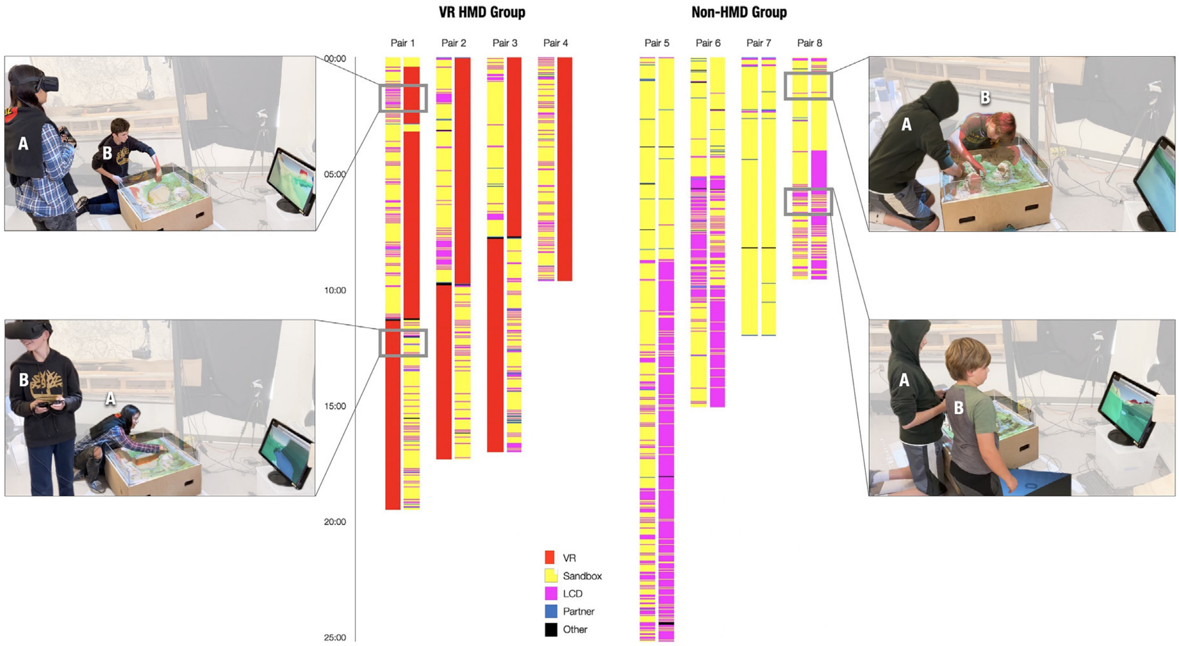


Fig. 4. What each child was looking at (i.e., VR using HMD, sandbox, LCD showing the VR view, partner, or other) for each pair during their second design session, color-coded in 2-second intervals. Each column represents one child. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(sculpting with sand, pointing, holding the VR controller, etc.) and what they were looking at (their partner, sandbox, VR view, etc. [Fig. 4]). Given the dynamic and embodied nature of the children's interaction with their partner, tools, and materials, we took a mixed-method approach by analyzing our data both quantitatively and qualitatively. We employed a microgenetic approach which examines moment-by-moment changes as they occur within relatively short periods of time to closely observe processes of change (Parnafes & diSessa, 2013). This approach allowed us to analyze the evolution of the children's design processes by studying their verbal and non-verbal communication consistently across pairs.

4.4.1. Children's gaze as a lens to study workflow and focus over time

For our first microgenetic analysis, we examined the gaze of the children as a way to estimate their workflow and focus. Fig. 4 shows what each child was looking at (i.e., VR using HMD, sandbox, LCD showing the VR view, partner, or other) for each pair during their second design session, color-coded in 2-second intervals.

5. Results

Fig. 4 shows the difference in terms of how the children in the two different groups worked with their partner. In the asymmetric VR HMD group (figures on the left), one of the two children was in the VR environment while the other child worked at the sandbox; therefore, the children in the VR HMD group did not share the same view during most of their work time because the child who wore the VR HMD was visually isolated from the physical environment. This asymmetric setup enabled the two children to assume different roles/tasks: the child at the sandbox became the maze builder while the VR child explored the VR maze. The change in the position of the vertical red bar highlights the moments that the pairs switched roles during their session.

Unlike the children in the VR HMD group who did not share the same view most of the time, the children in the Non-HMD group worked on the shared sand model together, sitting side-by-side as co-designers/builders (as seen in the picture above) rather than assuming different roles to each other.

Second, Fig. 4 shows the children's gazes in both groups at various times. In the VR HMD group, the children alternated between working at the sandbox and being in the virtual environment. When a child was at the sandbox, their gaze alternated frequently between focusing on the sandbox (marked by the bands of yellow) and focusing on the LCD that displayed their VR partner's perspective in real-time (marked by thin horizontal bands of pink over yellow) in all four pairs. This indicates that the children at the sandbox were regularly referencing the 2D virtual view for information about the virtual user's experience as they designed it.

In contrast, the pairs of children in the Non-HMD group focused on working at the sandbox first together, and did not look at the LCD heavily until almost halfway through (except for Pair 7 who did not use the LCD at all to explore their maze in this session). In other words, only when they were done making their sand maze model did the children in the Non-HMD group move on to explore their maze model using the handheld controllers and LCD. The end of their sand modeling was typically marked by the two children cleaning sand off their hands, and holding the VR controllers and the box in front of the LCD. Typically, one child held the controllers while looking at the LCD to navigate the maze while the other partner helped orient their location within the virtual world by looking at the "dot" projected onto the sandbox representing the maze user. Unlike the first group, the Non-HMD children did not continuously reference the LCD or virtual environment during the design phase and only used the LCD view as a means to explore their finished maze.

In summary, the children in the VR HMD group took turns sharing (or alternating between) two roles: designer at the sandbox and explorer in VR. The designer regularly referenced the other's view by alternating roles or by looking at the LCD. The Non-HMD group worked on the shared model together, and only explored (rather than referenced) their maze model virtually through LCD upon maze completion, creating two distinctive phases.

Table 1
Themes and categories used to analyze children's utterances. Overall percentage indicates the number of times those utterances appear out of the total utterances for each group (VR-HMD vs Non-HMD).

	Categories	Coding Thesaurus	Examples		VR HMD	Non-HMD	
Design Process	Plan	Expressing one's design plan, or stating one's desire to design in a certain way.	"Let's make a mountain here." "We need a 90-degree turn." "The mountain B needs to be three times as tall." "I'm making a mountain." "This path connects back to this." "Here is a dead-end." "This is the cliff."	Percentage	8%	23%	
				Chi-Square Test			Total
				Observed	110	226	336
				Expected	192.2	143.8	336
				Contribution	35.2	47	82.2
	Solutions	Offering a concrete design solution or an idea for a given problem or a situation.	"Let's make it taller." "The end (of the maze) could be at the top of the mountain."	Percentage	7%	2%	
				Chi-Square Test			Total
				Observed	87	19	106
				Expected	60.6	45.4	106
				Contribution	11.5	15.3	26.8
	Critique	Analyzing or assessing a design feature in a particular location or situation.	"The walls aren't that high." "There isn't really a path." "It's a little too shallow" "Water there."	Percentage	6%	1%	
				Chi-Square Test			Total
				Observed	76	11	87
				Expected	49.8	37.2	87
				Contribution	13.8	18.5	32.3
	Repair	Offering to mend or fix up an existing design feature.	"I'm gonna fix it." "Do you want me to make it shorter?" "I'll make a ramp instead."	Percentage	3%	0.4%	
				Chi-Square Test			Total
				Observed	39	4	43
				Expected	24.6	18.4	43
				Contribution	8	11.3	20
	Commendation	Act of providing the other with praise. Mostly directed to the partner (c.f., "celebratory," which could be personal or mutually experienced).	"That looks great!" "Nice hill." "So cute!" "That's cool!" "Good job!"	Percentage	5%	4%	
				Chi-Square Test			Total
				Observed	64	36	100
				Expected	57.2	42.8	100
				Contribution	0.8	1.1	1.9
	Evaluation	Making a judgment about the amount or value of their design.	"Is this tall enough?" "I'm gonna need you to come over here to see if these steps are way too tall." "Wait, do we have two cliffs?"	Percentage	3%	1%	
				Chi-Square Test			Total
				Observed	35	10	45
				Expected	25.7	19.3	45
				Contribution	3.3	4.4	7.8
	Conflict	Dispute or conflict between the two collaborators.	"Stop moving your hands!" "Stop it." "Don't do it!"	Percentage	1%	2%	
				Chi-Square Test			Total
				Observed	17	22	39
				Expected	22.3	16.7	39
				Contribution	1.3	1.7	3
	Agreement	Acknowledging the accordance in opinion or feeling.	"Yeah, that works." "Oh yeah that's a really big mountain." (in response to a partner's idea)	Percentage	4%	4%	
				Chi-Square Test			Total
				Observed	49	43	92
				Expected	52.6	39.4	92
				Contribution	0.3	0.3	0.6
	Glitching	Deviation from their tasks or tinker with the VR SandScape environment in ways that allowed new design possibilities and user experiences to emerge.	"Ahhh it's coming at you!" (moving a hand in the sand-box in front of the VR user's view). "See? (puts a hand in the sandbox) Look. I'm just building. I'm God! So I just "Godded" you!"	Percentage	3%	3%	
				Chi-Square Test			Total
				Observed	37	33	70
				Expected	40	30	70
				Contribution	0.2	0.3	0.5

(*continued on next page*)

5.1. Children's utterances as a lens into studying their work process

Next, we looked at the types of children's utterances, uninterrupted chains of speech, and how they varied between the two groups with respect to their non-verbal behaviors of gaze and turn-taking patterns. An initial open-coding approach enabled us to create emergent categories for how the children communicated with each other and engaged with their design process. Three core researchers jointly studied transcripts, field notes, and compared the work of different pairs across the data corpus. The researchers transcribed and coded each utterance individually, then came together to review categories. Open coding was used during the first phase of coding the transcripts, which means that coders generated their own labels for ideas, emotions, and concepts expressed by the participants. At this stage, an utterance could be assigned multiple labels by a coder to capture various messages conveyed by the participants. Some utterances received the label "No code," which included off-topic conversations (e.g., talking about friends and other school work) and "*Uh huh*"s and "*OK*"s. The coding thesaurus (see column 2 on Table 1) provided definitions that guided our coding process. When there were disagreements among the researchers, we discussed them as a group and iterated our coding schema until we reached consensus on common encompassing categories across the data corpus. Open coding continued until theoretical saturation was achieved, as indicated by the absence of new codes (Glaser, 1978).

A total of 24 different codes were independently generated during the first coding pass. Codes were collaboratively consolidated after the several coding passes based on their overlapping properties. Selective coding followed, which involved combining individual codes into preliminary hierarchical structures. To address statements that did not fit into our code reduction, we highlighted the code. Highlighted codes were used as temporary placeholders during this process when the researchers did not feel confident that any of the available codes successfully captured the statement. During the subsequent rounds of coding, the researchers coded each transcript independently using the selected codes agreed upon by the group. Codes were consolidated a second time to create a final list of 14 utterance categories. In summary, each transcript was reviewed 3 times

Table 1 (*continued*).

	Categories	Coding Thesaurus	Examples		VR HMD	Non-HMD	
Navigating Maze	Directing	Communication about wayfinding or orienting while navigating the maze.	"Where are you? / Where am I?" "Go to that mountain" "Follow the path." "You are at the top." "Keep going!"	Percentage	20%	27%	
				Chi-Square Test			Total
				Observed	265	266	531
				Expected	303.8	227.2	531
				Contribution	5	6.6	11.6
	Check in	Check in with the partner to see if they are on the same page.	"Do you see it?" "Are you OK?" "See that?" "Wait, what happened?" "Right there? OK."	Percentage	15%	13%	
				Chi-Square Test			Total
				Observed	201	132	333
				Expected	190.5	142.5	333
				Contribution	0.6	0.8	1.3
	Frame of Reference	Communication explicitly about one's standpoint or frame of reference.	"You see where my hand is? [point at a corner in the sandbox]" "You see where my giant finger is?" "Can you put your hand where the center is?"	Percentage	6%	2%	
				Chi-Square Test			Total
				Observed	74	22	96
				Expected	54.9	41.1	96
				Contribution	6.6	8.9	15.5
	Empathy	Expression of care towards the partner or well-being of the partner.	"Oops, sorry!" "Watch out." "Sorry" (in reaction to the partner critiquing e.g., "That's way too steep!") "Thank you" (for catching me)	Percentage	3%	0.4%	
				Chi-Square Test			Total
				Observed	35	4	39
				Expected	22.3	16.7	39
				Contribution	7.2	9.6	16.9
	Celebratory	Celebrating a success either jointly with the partner or individually.	"Yay!" "You made it!" "Voila! A mountain." "It's good now."	Percentage	2%	1%	
				Chi-Square Test			Total
				Observed	30	9	39
				Expected	22.3	16.7	39
				Contribution	2.6	3.5	6.2
	No-code			Percentage	15%	15%	

across 3 rounds of iterative coding. The resulting 14 categories of utterances varied in prevalence between the VR HMD and Non-HMD groups. To summarize and make sense of these differences, we further clustered the categories into two larger themes of children's communication about their making and design of the maze (*Design Process*) and their method of navigating the maze (*Navigating Maze*) (see Table 1).

The **Design Process** theme included categories of communication about ***planning*** (e.g., "*Let's make a mountain here*") and providing ***solutions*** (e.g., "*We can turn steps into a ramp*") for their designs. Through the process, the children encountered situations where they were in ***agreement*** (e.g., "*Yeah, that works*") or ***conflict*** (e.g., "*Stop it!*") with their partners and communicated their ideas through ***critique*** (e.g., "*Too steep!*") and ***evaluation*** (e.g., "*Is the wall high enough?*"), which led them to ***repair*** their ongoing designs (e.g., "*I'm going to fix it*"). The children also ***commended*** each other's work (e.g., "*Good job!*"), as well as finding creative uses of the SAR sandbox display through ***glitching***, a video game practice wherein individuals learn how to tinker with game systems to "mess with" other players and/or expand what is possible in the games they play. In general, the Design Process included communication about children's working and communicating with each other as designers.

On the other hand, the **Navigating Maze** theme focused on the children's use of the maze. The design task to build a maze that could be built at their school for them and their friends to go through, combined with the access to the VR and LCD views, prompted the children in both groups to test their designed mazes as users. As the children attempted to go through the mazes, the children gave each other ***directions*** (e.g., "*Keep going*") and in doing so, sometimes they needed to communicate their ***frames of reference*** (e.g., "*Do you see where I'm pointing at?*"). In the process, the children ***checked in*** with each other (e.g., "*Are you OK?*") and ***empathized*** (e.g., "*Sorry!*" "*Watch out. I might bump into you.*") and ***celebrated*** their navigation successes with their partner.

5.1.1. Statistical analysis

An analysis of the two themes and 15 categories (14 categories plus "no code" category) to show whether the VR HMD group engaged in discourses significantly different from the discourses of the Non-HMD group was performed using a chi-square test and an analysis of the contribution of each cell to the total chi-square.

The chi-square test demonstrated there is significant difference among the two groups (chi-square= 241.4494; df=16; P-value = 0.00001). The contribution of each cell to the total chi-square showed that differences lies in the Non-VR group, which performs to a lesser extent than the VR HMD group when it comes to **solutions** (chi-square contribution = 26.8), **critique** (chi-square contribution = 32.3), **repair** (chi-square contribution = 20), **empathy** (chi-square contribution = 16.9), and **frame of reference** (chi-square contribution = 15.5). The main difference where the VR group performs to a lesser extent than the Non-VR group is in terms of utterances about a **plan** (chi-square contribution = 82.2).

5.1.2. Design process

Within the theme of Design Process, **planning** utterances such as "*Let's make a mountain here*" were most frequent for both the Non-HMD group (22%) and the VR HMD group (7.5%). The children communicated with each other about what they were planning to make at the sandbox, which became the basis for agreeing with each other or critiquing their ongoing work and resolving their differences.

Yet there were differences within the Design Process, which pointed to differences in work styles in their design process. Overall, the VR HMD group had more constructive communication about **solution**, **critique**, and **repair** than the Non-HMD group. These differences seem to come from the way the VR HMD group questioned their ongoing design work from asymmetrical perspectives. In one example in Table 2 (left column), Olga, immersed in the virtual environment, critiqued the slopes she was experiencing in VR (e.g., "a little steep," "really steep"), which led Ron at the sandbox to immediately "fix" the slopes so that Olga could go down with ease. Ron shifted his attention between the LCD and the sandbox in order to respond to Olga's critique and repaired the maze. This asymmetric setup with two different perspectives (in VR vs. directly looking at the sandbox) and roles (user vs. designer/builder) seemed to result in their maze design

Table 2
Transcripts and images of the children in two different groups during their **Design Process**. The "gaze" column in each group shows what the children were looking at while they worked.

VR HMD group			Non-HMD group		
Speaker	Gaze	Transcript	Speaker	Gaze	Transcript
Olga	VR	Down? [turns and follows R's directions]	Zac	sandbox	There's a 90-degree turn here.
Ron	LCD	[looking at Olivia's view] Yeah, just follow that.	Joe	sandbox	We also have the option this way [working with sand]
Olga	VR	A little steep.	Joe	sandbox	Yeah.
Ron	LCD	Yeah, sorry! You can go down.	Joe	sandbox	More of the two 90-degree turns.
Ron	sandbox	I just fixed it. [as he fixes the landscape]	Zac	sandbox	OK I think we can put the mountain here.
Olga	VR	OK.	Joe	sandbox	Or we could have… [sculpting with sand]
Ron	LCD	Yeah it's really steep.	Joe	sandbox	Oh, is this our second mountain here?
Olga	VR	It's a little rough.	Zac	sandbox	Yeah.
Ron	LCD	Water all over.	Zac	sandbox	We could make… two mountains there.
Olga	VR	It's' a little steep on the mountain [laugh]	Joe	sandbox	I thought you were building them over here.
Ron	LCD	Oh yeah. Let's change it.	Joe	sandbox	Is that your... dead-end?
Ron	sandbox	It (path) goes all the way to the side.	Zac	sandbox	Oh yeah.
Olga	VR	I'm going to wait at the water.	Joe	sandbox	Dead-end.

to be constantly critiqued and iteratively improved upon as it was being built.

For the Non-HMD group, the same perspective shared by both children seemed to invite them to work symmetrically at the sandbox first, even though the 2D VR view on the LCD and the controllers were introduced to them and available from the beginning. The Non-HMD children worked shoulder-to-shoulder while sharing the physical sandbox workspace and looking at it together during their design process (picture in Table 2, right column). As seen in the example below, the children discussed what they were building together, but they used less **critique** and **solutions** when compared to the VR HMD group. Working side-by-side in parallel at the sandbox seemed to limit questions or disagreement about their ongoing work, as if they implicitly understood the other's (same) perspective as they jointly planned and built their model.

While a small sample, we observed different interaction styles among the two groups, whether the children were sharing the same perspective (Non-HMD group) or accessing their design from multiple different perspectives (VR HMD group). Having one of the children in 3D VR experiencing their design as a user as it was being built, seemed to orient their work towards **critique**, **evaluation**, and **resolution**. On the other hand, working shoulder-to-shoulder with their partner as they share the same perspective of workspace seemed to focus their activity on building the model without worrying about the potential users of their maze.

5.1.3. Utility of navigating the maze

Within the theme of Navigating Maze, **directing** utterances such as "*keep going*" or "*follow the path*" were most frequent for both the Non-HMD group (26%) and the VR HMD group (18%). Yet the two groups differed in the way they navigated their maze as it was a joint experience with a shared view and controllers for the Non-HMD group, but it involved coordinated efforts between two different views and roles for the VR HMD group.

As discussed previously, the Non-HMD group did not navigate their models until after they had fully finished building the models. They often did not touch their sand models again during nor after their exploration. Therefore, the actual use of their mazes seemed distinctive from their design activity. The children in the Non-HMD group navigated their mazes together from the shared perspective of being outside of the mazes, controlling the "dot" in a similar style to how one might drive a remote-controlled car from the outside of the track the car is on. When they were unclear about their location or orientation in the mazes, they pointed at specific locations directly in the sandbox or LCD using their hands so that their partner could see it. In the example below, Liz and Quin (Table 3, right column) held the controllers together and directed each other in the shared navigation experience (e.g., "*go straight*" or "*wrong way*"). Their language indicates that, for them, navigation was more about exploring their finished product as a reward rather than evaluating it.

On the other hand, in the VR HMD group, the pairs did not simultaneously explore the environment from the same perspective but navigated immediately, using navigation as a way to test their design intermittently. Only the VR child who wore the HMD navigated, and their position was projected as a "dot" in the sandbox. In the example below (Table 3, left column), Lee navigated the maze in VR while Alex at the sandbox guided Lee by looking at the "dot" in the sandbox representing Lee and the LCD showing Lee's perspective. In order to help Lee orient himself in VR, Alex used his hand in the sandbox as a shared reference point that bridged the physical world Alex was in and the virtual world Lee was immersed in (Alex: "*head towards where my hand is*"). This required Alex to understand the difference between how he was navigating the maze by looking at the "dot" and LCD, and how Lee was navigating the same maze as the "dot." This explains why the VR HMD group explicitly communicated their **frame of reference** more frequently (5.6%) than the Non-HMD group (2.2%). In the example with Lee and Alex, instead of treating navigation as a mere exploration or game, they used it to help inform their design and learn about navigational challenges.

Table 3
Transcripts and images of the children in two different groups during their **navigation process**.

VR HMD group

Speaker	Gaze	Transcript
Alex	sandbox	[to Lee] OK, so there's going to be a bit of a path.
Alex	sandbox	Like right here [points with his hand in sandbox]
Lee	VR	Right, I see where your hand is. OK.
Alex	LCD	So there's going to be a bit of a path up the mountain that is not so steep.
Alex	LCD	So you go to the side of it.
Alex	LCD	Otherwise, it might be too steep.
Lee	VR	That's actually perfect! Not steep at all.
Alex	sandbox	So now. Now, head towards where my hand is.
Alex	sandbox	Because this is where the path is.
Lee	VR	I know.
Alex	LCD	Oh no. Actually, you are right. Now you are on the path. So...
Alex	LCD	I think the mountain is too steep otherwise, but...
Lee	VR	It's not that steep at all really. You can get up.
Alex	LCD	So now you are on top of the mountain, don't jump off this time.

Non-HMD group

Speaker	Gaze	Transcript
Liz	LCD	That's our big water.
Quin	LCD	The path looks so cute!
Liz	LCD	And that is that at the front. And that's our little mountain.
Quin	sandbox	OK, Let's go there.
Liz	sandbox	Yeah? OK.
Liz	sandbox	So 'straight' should be towards the mountain?
Liz	LCD	Where are we?
Quin	sandbox	We are right at the ...
Liz	LCD	OK, over the mountain
Liz	LCD	Wrong way [turning the controller box]
Quin	LCD	Good job.
Quin	LCD	Wait. Are we at the top?
Liz	LCD	Yes. Almost.
Liz	LCD	Try your, a little towards right?

Therefore, the two groups seemed to view the navigation and control of the "dot" differently. In the Non-HMD group, the children typically navigated the maze at the end as a "finishing reward" and they moved as if they were exploring the completed terrain via a remote-controlled vehicle (c.f., "Mars rover"). In contrast, for the VR HMD group, the "dot" represented their flesh-and-blood partner and not a mere marker. The VR HMD group thus seemed to treat the "dot" as a representation of their partner actually going through their maze design and treated navigation as a tool to learn about movement challenges, and carefully made modifications. This might also explain why the VR HMD group exhibited more **empathy**, e.g., "Sorry!" "Watch out. I might bump into you" (3%) than the Non-HMD group (0.4%).

5.1.4. Shifting between inside and outside perspectives vs. Using concurrent perspectives

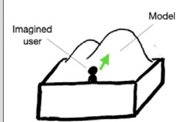
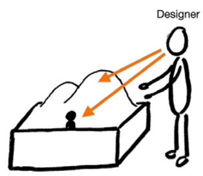
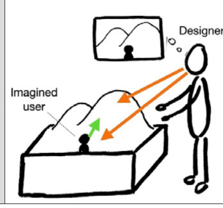
Using our VR SandScape system, both groups worked with the scale differences between how their model at the sandbox looked to them in person vs. how the same model appeared from the perspective of the virtual user/dot (displayed either on the VR HMD or the LCD). In other words, the children immersed in VR utilized the perspective of being **inside** of the model in the 1:1 scale (e.g., "*I'm climbing the mountain*") and the children at the sandbox utilized the perspective of being **outside** of the model looking down at the maze in the 1:43 scale (e.g., "*The two paths can meet at this point*"). Using this **inside** vs **outside** framework can further support the argument that allocentric views were being utilized, because if a child is able to access both **inside** and **outside** perspectives despite only being at one physical location, then allocentric views must be present.

Returning to our discussion about the difference between **egocentric** views and **allocentric** views, to experience the virtual terrain from inside as a user is to utilize an egocentric view ("a world seen from my perspective as a user"). Similarly, working at the sandbox and looking at the maze design from **outside** is also utilizing an egocentric perspective ("a world seen from my perspective as a designer"). Neither of these perspectives individually require an allocentric perspective ("a world seen from another's perspective"). Thus, although the children took on different roles, it would have been possible for them to only use egocentric perspectives if they only accessed the perspective relevant to their respective station. On the other hand, accessing **concurrent inside & outside** perspectives simultaneously would require **both** egocentric and allocentric views as one needs to acknowledge multiple perspectives that involve how things look from another's perspective as well as one's own. If the children were able to access the viewpoint of the other while also working from their own, they must have used an allocentric perspective. For example, in the example shown in Table 3, Alex instructed Lee to take a certain path because "*otherwise, it might be too steep*" for Lee to climb up. Even though Alex was not in VR, Alex imagined what the experience might be for Lee to go through the maze as a user. This requires consideration for both **inside** perspective (imagining the maze user) and **outside** perspective (imagining oneself as a designer looking at the model in the 1:43 scale) simultaneously.

In order to study how the children in the two groups moved between working from the perspective of the designer, the user, and sometimes both simultaneously using an allocentric view, we further analyzed the children's utterances in terms of which perspective they were speaking from. The three core researchers further coded every utterance in our data corpus and labeled whether the children were speaking from: **inside**, **outside**, or both **inside & outside** simultaneously (**concurrent inside & outside**). Table 4 summarizes the results.

The analysis compares the groups of children in VR HMD vs. Non-HMD by evaluating whether the children in the VR HMD group engaged in perspective-taking discourses significantly different from the perspective-taking discourses of the Non-HMD group. To better understand this difference, we use a chi-square test and an analysis of the contribution of each cell to the total chi-square. The chi-square test demonstrates there is a significant difference among the two groups (chi-square= 583.5; df= 3; P-value = 0.0001). The contribution of each cell to the total chi-square shows that one of the primary differences lies in the **outside** perspective, where the Non-HMD group performs more

Table 4
A summary of three different perspectives: **inside**, **outside**, or **concurrent inside & outside** (both inside & outside considered simultaneously).

Categories		Definition	Examples
INSIDE	**1:1 scale**, User's perspective **Egocentric** 	Communication about how it feels from the 1st person/ user perspective. Speaking from the person who is inside of the maze.	A child who is immersed in VR, she sees a mountain in front of her as part of his maze, and says, "Oh wow!" "I'm going up the hill." Two children are navigating the maze together using the LCD and VR controllers but without VR HMD. One child says, "OK, we made it. We are inside."
OUTSIDE	**1:43 scale**, Designer's perspective **Egocentric** 	Communication from the perspective of the designer who is working on the model, typically looking down at the sandbox.	A child who is working at the sandbox, looks and points at the shape of the paths she just created as part of her maze, and says, "It's (looks like) an avocado!" A child who is sculpting shapes with sand in the sandbox, tells his partner, "I'm making a dead-end." A child who is working at the sandbox, looks at the mountain she just created on the LCD and says, "It's so cute!"
CONCURRENT INSIDE & OUTSIDE	Both **1:1 scale** and **1:43 scale**, User's and Designer's perspective simultaneously Mix of **Egocentric** and **Allocentric** 	Communication that requires acknowledgment of multiple different views, i.e., both inside (user's) and outside (designer's) views simultaneously. Utterances that acknowledge the differences between the two or more perspectives or the scales concurrently.	A child who is working at the sandbox tells the child who is immersed in VR, "You see where my giant finger is?" (e.g. finger is represented in VR terrain) Two children are navigating the maze together using the LCD and VR controllers but without VR HMD. One child tells her partner, "Just put your finger on. Because it's messing up. Just like straight up. Try not to put your arm in. I just want to see the point." A child who is working at the sandbox tells the child who is immersed in VR, "It's (the slope is) very steep right?"

INSIDE

	VR HMD	Non-HMD	
Percentage	12%	13%	
Chi-Square Test			Total
Observed	155	126	281
Expected	161	120	281
Contribution	0.2	0.3	0.5

OUTSIDE

	VR HMD	Non-HMD	
Percentage	8%	49%	
Chi-Square Test			Total
Observed	100	488	588
Expected	336	252	588
Contribution	166	222	388

CONCURRENT INSIDE & OUTSIDE

	VR HMD	Non-HMD	
Percentage	59%	21%	
Chi-Square Test			Total
Observed	775	209	984
Expected	563	421	984
Contribution	80	107	186

than expected (chi-square contribution = 222.1) and the VR HMD group performs less than expected (chi-square contribution = 166.1). The Non-HMD group performs less than expected in the **concurrent** perspective and more than expected in the **inside** perspective. The VR HMD group performs more than expected in the **concurrent** perspective and less than expected in the **inside** perspective.

Our analysis showed that both VR HMD and Non-HMD groups engaged in the **inside** perspective equally often in their communication with their partner. This is interesting as it suggests that while the Non-HMD group could not use any VR HMD, the Non-HMD children did explore and talk about their design from the user's perspective in the 1:1 scale via the VR view shown on the LCD. In other words, the two groups experienced the virtual maze user's perspective equally often regardless of the method of access to the VR view (i.e., via VR HMD vs. LCD). This is an egocentric view.

Our analysis showed that the Non-HMD group communicated from the **outside** perspective significantly more often (4 times more) than the VR HMD group. In other words, the Non-HMD group was looking at and talking about their design from the designer's perspective more often than the user's perspective (4 times more). This aligns with the earlier finding of the Non-HMD group spending more time on **planning** (e.g., "*Let's make a mountain here*") (22%) compared to the VR HMD group (7.5%) and viewing the dot as an object rather than as a person. This is also an egocentric view.

On the other hand, the VR HMD group engaged in the **concurrent inside & outside perspectives** significantly more than the Non-HMD group (59% vs. 21%), which we previously established indicates the use of allocentric views. The example transcript below shows how the VR HMD group coordinated both perspectives. In the example in Table 5, Sam at the sandbox communicated explicitly about what she was building so that Ruth whose view to the sandbox is occluded by VR HMD could still understand what Sam was describing. These findings show Sam's sensitivity to both in & out perspectives concurrently. When Ruth in VR HMD critiqued part of their sand model in progress (Ruth: "*These stairs are a lot tall*") spoken from the inside perspective, Sam immediately compared the maze model from her designer's perspective (outside perspective, looking down at the sand model) as well as the user's perspective simultaneously (inside perspective, looking at Ruth's VR perspective via LCD). In Sam's response utterance, we can see how Sam explicitly acknowledged the difference between the two perspectives: "*Sorry. They* [stairs] *look very short in real life* (i.e., from an egocentric view of the designer). *But maybe not* (from an allocentric view of the user)."

Sam, the designer at the sandbox, was able to consider the virtual user's perspective because of her partner experiencing her design from "inside" as it was being built. This led Sam to revisit and evaluate features of her maze design and ultimately repair them to improve the user's experience, thus leading her to use the **concurrent inside & outside** perspective and an allocentric view.

The Non-HMD children also took both the roles of designer (outside perspective) and user (inside perspective), but sequentially rather than concurrently as in the VR HMD group. For the Non-HMD group, as discussed earlier, the design phase and the navigation phases were two distinctive activities that happened in sequence. As a consequence, the Non-HMD group tended to look at their maze mostly from outside designer's perspective jointly with their partner at the first half of their session, and then switched to the inside perspective for the latter half of the session when they moved on to navigating their maze together which used only egocentric views. The sequenced work style did not seem to lead the Non-HMD group to consider the concurrent in & out perspective involving allocentric views. Therefore, the simultaneity of critique and designing present in the VR HMD group seems to contribute to a more concurrent inside & outside

Table 5
Transcript of a pair of children in the VR HMD group coordinating their perspectives.

Speaker	Gaze	Transcript	Perspective	Description	Code
Sam	sandbox	Let's start right here [places her hand in the sandbox] I'll make the starting point.	In & Out	Sam places her hand in the sandbox so that Ruth can see where Sam means by "right here."	Plan
Sam	sandbox	We'll have to make the stairs though, because… can't really get …	In & Out	Sam uses the pronoun "we" as she builds the sand model and anticipates the user's perspective.	Solution
Ruth	VR	[looking in VR] You could just make like a ramp	In & Out	Ruth suggests a design solution to Sam. Ruth is holding the VR controllers to navigate in VR so Ruth cannot execute her idea to build the ramp. Both in & out views needed.	Solution
Sam	sandbox	Yeah.	No code		No code
Ruth	VR	Speaking of stairs, these stairs are a lot tall.	In	Ruth shares her perspective from inside.	Critique
Sam	partner	[Sam looks at Ruth]	No code		No code
Ruth	VR	They are just really tall! [looking up in VR]	In	Ruth shares her perspective from inside.	Critique
Sam	LCD	[Sam looks at LCD]	No code	Sam looks at the LCD to check how the maze looks from Ruth's perspective.	No code
Sam	sandbox	Sorry. They look very short in real life. But maybe not. OK.	In & Out	Sam is comparing how it looks to her from the perspective of a designer while acknowledging Ruth's perspective.	Frame of Reference
Sam	LCD	OK. Let's see. OK. one second. Let me fix that. Right there.	In & Out	Sam is checking how her repair looks from the user's perspective.	Repair
Sam	sandbox	Kind of look like tall steps, too. But… OK. Alright.	In & Out		Frame of Reference

Table 6
Transcripts and images of the children glitching in two different groups.

VR HMD group

Speaker	Gaze	Transcript
Gus	sandbox	Do you want me to just ...
Finn	VR	Yeah, Make it like..., acting like a ramp
Gus	sandbox	Here...
Gus	LCD	Yeah.
Finn	VR	Oh my god. There is a spike like … [reacting to the part of Gus' hand appearing in VR]
Finn	VR	Make it so that I can climb on your arm
Gus	LCD	I'm trying to…
Finn	VR	No. Lower your arm and make it ramping off the sand.
Finn	VR	Is that what you are doing?
Gus	LCD	Yup.
Gus	sandbox	You did it! You are on my arm!
Finn	VR	Oh my god! Ahhh...
Finn	VR	I'm on this way.

Non-HMD group

Speaker	Gaze	Transcript
Ike	LCD	I can see your hands though, so I think I am close.
Tom	LCD	Oh yeah, there's my hand.
Tom	sandbox	See? [puts hand in sandbox] Look. I'm just building. I'm God. I am just building.
Ike	LCD	Look, I'm going over mountain. Look I'm going over mountain.
Tom	LCD	Wait. God? [puts hand in sandbox]
Tom	LCD	[Laugh] God killed you!
Ike	sandbox	All right. I'm on top. This is the top of the mountain. This is the top...
Tom	sandbox	You are on top of the mountain.
Tom	LCD	God! [puts hand over I in VR]
Ike	LCD	[laugh] Climb up, you can do it!
Tom	sandbox	[Looking at the sand and in a deeper voice] Here's a little dead end right here. Cause I'm trying to make your life miserable.
Ike	LCD	Alright, I go this way.

perspective. The VR HMD group engaged in a mix of allocentric and egocentric views in their design process more than the Non-HMD group did.

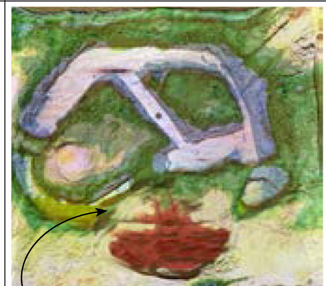
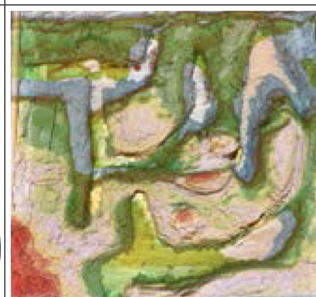
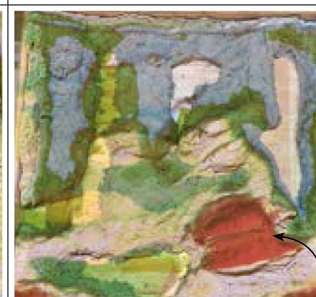
5.1.5. Glitching user experience

A category in our analysis that unexpectedly emerged was how the children learned to "glitch user experiences" throughout their design process in both VR HMD (2.8%) and Non-HMD (3.3%) groups. Glitching in video gaming contexts involves individuals tinkering with video game architectures by learning to manipulate system errors (Consalvo, 2009; Rivero & Gutiérrez, 2019). Through glitching, gamers can expand the boundaries of what is possible in the games they play. We drew on this notion of glitching to conceptualize the design activities that we observed from children in our study when they went beyond our design challenges and used the technologies we provided in ingenious yet unconventional ways. Specifically, children in both groups glitched user experiences by manipulating the "dot" representation on the sandscape. However, although we observed children glitching in both groups, the Non-HMD group tended to perform a playful form of glitching while the VR HMD group displayed a collaborative and generative form of glitching.

The first form of glitching that we categorized as "playful," seen mostly in the Non-HMD group, involved children deviating from our design challenges to "mess with" the experiences of their partners. In the example below in Table 6, right column, drawn from one of the Non-HMD pairs, we see a child at the sandbox fascinated by his ability to "play God" with his partner's experience.

We categorized this example as a less productive form of glitching in that it did not afford new possibilities for the VR user or the designer in the sandbox. Rather, this form of glitching

Table 7
An example evolution of maze designs of one pair from each group over three sessions.

	Session 1 Create a maze with one mountain and a 90-degree turn.	**Session 2** Create a maze with two mountains of different height.	**Session 3** Create a maze with three mountains of different height and a cliff that is thrilling but safe.
VR HMD Pair 1	 Many paths in complicated meandering patterns. One path goes directly through a peak of a mountain.	 Significantly simpler design compared to Session 1 with much fewer number of paths that are wide with much fewer twists and turns.	 The design remains simple with defined wide paths. A path over the mountain is slightly below the apex, rather than directly going through it.
Non-HMD Pair 1	 Paths with twists and turns. Pathes go directly through a peak of a mountain.	 Many paths with twists and turns. In addition, many dead ends are added to their design compared to Session 1.	 The overall approach to design with many dead ends remains similar to Session 2. One path goes directly over a peak of a steep mountain.

reinforced the control hierarchy between the Sandscape designer and the maze user. As the transcript reveals, Tom acts as "a God" in the virtual world that Ike is trying to navigate, which reinforces how the Non-HMD group viewed the dot as an object rather than as a flesh-and-blood partner.

We categorized the second form of glitching seen mostly in the VR HMD group as "productive" (shown in Table 6, left column) because it was a co-constructed design experience between the VR user (Finn) and the Sandscape designer (Gus). In the example, we see how the VR user (Finn) tells the Sandscape designer (Gus) to use his hand as terrain so that Finn could climb on it. Although this was not part of the design challenges that we provided the children, Gus and Finn managed to design a novel user experience for Gus by glitching the depth-sensing cameras with his hand. As such, the pair expanded how the user participated in the VR simulation. This form of co-constructed glitching allowed the researchers to learn more about the possibilities of the VR SandScape in relation to design and user experience. In this case, Gus employed an allocentric perspective in his design by using his arm as a tool to co-construct a novel experience for Finn, creating new possibilities for how Finn could participate in the VR world.

Children used glitching as a design practice for their creative expansive experiences, almost resembling a video game experiences (e.g., being "killed" by an unexpected protagonist), which went beyond the maze design tasks. Through their glitching activity, we were able to see how children in the VR HMD groups shifted from egocentric to allocentric perspectives as they leveraged glitches to design new experiences for VR users. These findings reveal how children played, interacted, and repurposed the tools we provided for them in ways that were unexpected to the researchers. As such, the category of glitching emerging in our analysis shows us that children continue to blur the boundaries/limits of user experience in ingenious ways. While it is beyond the scope of current work, in future work, we will more closely study the role of glitching in the design process of youth and how glitching may contribute to ways youth design for user experience.

5.2. *Differences in design outcomes*

How might the differences in the children's perspective-taking, maze navigation, and design processes between the two groups influence their design outcomes? We tracked the children's maze design outcomes over the three sessions to see if there are any observable differences in their maze designs over time.

Overall, we observed differences in maze complexity between the two groups. Table 7 shows an example evolution of maze designs of one pair from each group. In the first session, we observed that both groups' maze designs generally started out creative yet ambitious with many paths, turns, hills, and valleys (see "Session 1" column for both groups). However, for the VR HMD group, the subsequent design in the next session became simpler with fewer elements, while the subsequent design remained complex for the Non-HMD group.

For the VR HMD group, the differences between the first session and second session show a reduction in the number of paths, opting for paths that go around a steep hill instead of going against it, more clearly defined paths, and overall simplicity in their maze design (see VR HMD "Session 2" column in Table 7). This is interesting because in our study, all children were asked to include more elements in their maze design in each subsequent session (e.g., build 3 mountains of different height in the maze in session 3 compared to 2 mountains in session 2 and 1 mountain in session 1). Despite these increased challenges, the VR HMD group's designs seemed to become simpler while still fulfilling the challenge requirements.

Table 8
Number of children circling "YES" to a question, "Would you like to make any changes to the maze model?"

	Session 1	Session 2	Session 3
Number of YES responses for VR HMD group (8 children total)	5	6	5
Number of YES responses for Non-HMD group (8 children total)	3	2	0

Table 9
Average scores for a Likert scale of "5: Looks great" to "1: Needs work."

	Session 1	Session 2	Session 3
VR HMD average (8 children total)	3.75	2.94	3.88
Non-HMD average (8 children total)	4.13	4.31	4.38

The simplification may be explained by the asymmetric work pattern in the VR HMD group. As discussed in the previous section, having the asymmetric roles of a designer and a user at all times during their sessions, the VR HMD group children noticed that parts of their design felt challenging ("*path is too narrow*," "*walls are not high enough*," "*there isn't really a path*," "*very steep*," etc.) to navigate in practice and were thus motivated to make voluntary design changes. For example, well-defined paths were created because they thought about the accessibility for a VR-user/future user. Such changes led the VR HMD group's design to become simpler over time, prioritizing the need of the maze user over their initial playful and aspiring ideas. As discussed in Section 5, the VR HMD group had more communication involving **critique** (6% for VR HMD group vs. 1% for Non-HMD group) and **repair** (6% for VR HMD group vs. 1% for Non-HMD group).

For the non-HMD group, by looking at the progression from sessions 1 through 3, the design seemed to become slightly more intricate as the tasks involved more challenges. Their mazes remained complex and playful with many paths that lead directly up against the steep mountains, multiple twists, turns, and dead ends. Their mazes seemed to be designed for entertainment and challenge rather than usability.

5.3. Children's own evaluation of their maze models

Thus far, we have presented our analysis of the children's design activities. Now we turn to the children's subjective experiences in working with the VR SandScape system. We were interested in studying the children's satisfaction or dissatisfaction with their work and how much additional work they felt was needed for satisfaction. At the end of each session, we asked all of the children to fill out a short survey with two questions on a piece of paper. Each child filled it out individually and did not see each other's responses.

- The first question asked, "Would you like to make any changes to the maze model? Circle YES or NO."
- The second question asked, "How would you evaluate your final maze model?" Using a Likert scale of "5: Looks great" to "1: Needs work," the children were asked to circle their answers individually.

Tables 8 and 9 show the results.

Overall, more children in the VR HMD group indicated that they would like to make changes to their design than the children in the Non-HMD group, even from the very first session. Over time, the desire to make changes remains high for the VR HMD group while decreasing for the Non-HMD group. Most strikingly, in session 3, five out of eight children in the VR HMD group responded "Yes" to changing their design compared to zero out of eight children in the Non-HMD group. The desire to iterate and improve their design work, therefore, seemed to be higher in the VR HMD group.

The second question asked, "How would you evaluate your final model?" Overall, the children in the VR HMD group were more critical of their design compared to the children in the Non-HMD group in all three sessions. The VR HMD group felt that their design needed more work in session 2 than session 1, but their self-evaluation improved in session 3. In contrast, the Non-HMD group's self-evaluation of their design improved consistently over time.

In summary, the VR HMD group initially felt more constructively critical about their design and felt that their design needed more work than the Non-HMD group. The Non-HMD group felt more satisfied with their design and felt their design was more complete (i.e., "No need to make any changes"). Having the experience of being immersed in the environment made the VR HMD group more able to see the problems with the maze and gave them ideas for changes. As such, the VR HMD group drew on their experiences of being immersed in the virtual environment to examine problems with the maze and to develop new ideas for how to make improvements in their design.

5.4. Utility of the VR view (via either 3D HMD or 2D LCD)

Finally, we asked the children about their subjective feelings towards the usefulness of the VR view. After the design session, we verbally asked all the children whether the VR view (accessed through an HMD and an LCD for the VR HMD group vs. accessed through an LCD for the Non-HMD group) was helpful.

Overall, all eight children in the VR HMD group found the VR HMD view helpful, while six out of eight children found the VR view (through the LCD) helpful in the Non-HMD group. In addition, there was a qualitative difference in how the children in each group found the VR view (via either 3D HMD or 2D LCD) to be helpful.

The VR HMD group described using the VR HMD view as an opportunity to encounter and notice design improvement possibilities for future users. Example quotes below are VR HMD group children's individual answers to the question, "Was VR view helpful?":

Gus: Yeah [the VR HMD view] it's helpful. Because it's giving a **natural view** of it. If you just looked at it (from the sandbox), it looks cool, but **you didn't really experience it yourself**. So experiencing it yourself (through the VR HMD view), you have fun with it. But then, **what can we change**? Like **I would change** here, make it taller. So that we feel, "Oh wow, we really feel like we are in a **natural** canyon."

Finn: Well, the bird's eye view is helpful because you can see everything (pointing at sandbox). In VR it is helpful **when you want to make certain places better**. You can go to that place (pointing at sandbox) and **see what's wrong**.

Sam: I think it [the VR HMD view] helps **make everything to scale**, to **make sure that we can actually get around the maze**.

Ron: It made it easier for the person to **see what the problems were**. The VR person can tell you "Oh these walls are not deep enough. I can't tell if these are just trails or open plains."

Lee: VR kind of makes it feel like it's in **someone else's eyes**. In **an actual person's eyes**. A person who jumps around where it's landscaped.

Gus talked about the difference between just "*looking at*" the maze vs. "*experiencing it yourself.*" Experiencing it from the VR perspective allowed him an opportunity to consider changes in his design. Ron and Finn both talked about the VR view allowing them to go to a particular place to "*see what's wrong*" so that they can improve it. Sam was concerned about whether or not her design allowed users to "*actually get around the maze*." These children moved between VR view and sandbox as a way to diagnose and solve problems in their design, which was different from the Non-HMD children's approach.

In contrast, the Non-HMD group described the merit of the VR view shown on LCD as a wayfinding tool and providing a *"cool"* view rather than a diagnostic tool. Example quotes below are Non-HMD group children's individual answers to the question, "Was VR view helpful?":

Tom: [The VR view] It was just good to see **where we were on the map**. And it was **cool** to see the **3D perspective**.

Quinn: [The VR view was helpful] Cause we know **which direction we need to go**, like **what direction we are facing**. So we can turn the box to face wherever we are going.

Zac: [The VR view] Not really [helpful] while building it. Because building it is kind of easy to visualize here (pointing at the sandbox). But it [the VR view] was **cool** for like, looking at it.

For the Non-HMD group, the VR view shown on LCD was helpful in navigating their maze with the additional "*cool*" view *after* they had finished their model but not helpful while they were building their maze, as evident in Zac's opinion above. In contrast, the VR HMD children explicitly mentioned that the VR view enabled them to experience the maze from a different perspective ("*someone else's eyes*") during the design process. For the VR HMD children, the VR view was not just an alternative cool view but was a view that invited them to find possible areas of improvement during the design process that they did not notice before, which led them to actively change their design. This explains why the VR HMD group felt more critical about their design than the Non-HMD group, as well as why the VR HMD group's maze design changed over time to reflect their observations and improvements.

6. Discussions

In our VR SandScape setting, children who had access to virtual immersion leveraged this technology to develop multiple perspectives, which had an impact on both the processes and outcomes of the middle school children's collaborative design projects. To the VR HMD children, having access to a different scale and perspective from reality meant that they continuously engaged in asymmetric collaborations where the two children took turns being the designer at the sandbox with the outside perspective and the user who experienced the design from the inside perspective in VR. Effectively, the tiny moving "dot" projected on the sandbox represented a flesh-and-blood partner (the VR child) experiencing their ongoing maze design at a 1:1 scale, and it also served as a *proxy* for possible users beyond themselves, similar to the findings from the participatory design with children (Metatla et al., 2020). In doing so, the children coordinated what they saw from their respective egocentric perspectives while concurrently considering allocentric perspectives (i.e., how the "other" sees the maze, how different objects look from different points of view, etc.). The ability to coordinate multiple different perspectives and confront one's own perceptual bias from another's perspective (allocentric view) seems to contribute not only to learning content but to cognitive and moral development as well (Schwarz & Baker, 2017). In the process, the VR HMD group changed their design to respond more to the needs of the maze user, using navigation and gaze as tools to test their designs intermittently. As an outcome, their designs gradually became simpler and more empathetic towards the users' needs, perhaps at the expense of some of their original liberal creativity but incorporating more user-centered features such as wider paths and less steep hills to climb. The immersion of VR helped them be attentive to details that otherwise go unnoticed or are not well comprehended (Youngblut, 1998).

In contrast, the Non-HMD children's physical proximity to their partners and shared field of view allowed them to effortlessly engage in joint-activity on the shared sand model. Non-HMD children focused on building the sand model together first, and then moved on to exploring their finished model using the VR controllers and the LCD in a sequential manner. They seem to naturally understand each other's perspectives as they shared the same view of their workspace and did not seem the need to consider allocentric perspectives (i.e., how the "other" inside of the maze sees and experiences, or how different objects look from different locations, e.g., how the "avocado" in the maze actually feels like when going through it as a user, etc.). They did not appear to feel a need to imagine an actual maze user's perspective or needs, likely because the LCD was merely a window into the user's perspective rather than an immersion. While navigating, the VR view on LCD seemed to give them assurance for how their maze design visually appealed to them (e.g., [looking at a mountain] *"It's so cute!" "It's an avocado!" "Looks cool!"*). Navigation was a fun activity and reward at the end of the task rather than a need-finding tool. Their maze designs over multiple sessions consistently involved interesting twists, turns, ups and downs. They seemed to enjoy their design process (e.g., *"I'm God! I'm just building"*) and felt a sense of empowerment through their freedom to create. They remained the observers of their design as opposed to the experiencers from within.

The Non-HMD children were more immediately satisfied with their design compared to the VR HMD group, perhaps because they were designing for fun rather than functionality. In contrast, the VR HMD children were less immediately satisfied with their design and wanted to continue making changes to their design to improve user experience. In the post session interviews, the VR HMD children frequently mentioned a sense of *"wrongness"* involved in their design and how seeing their design in VR helped them make things *"better."* Such reflections and self-critique were not mentioned among the Non-HMD children. As the sessions progressed, the VR HMD children approached their design as something to be experienced and constantly improved upon after the initial construction. They treated design as an iterative problem-solving process with a future user in mind (allocentric perspective). In many ways, this approach is similar to the professional design process. Once user experience designers notice a problem from a user's perspective, they naturally wish to design a more usable solution. As famously stated by many professional designers, "Design is never done." There is always something to improve as designers strive for more perfection and as the children in the VR HMD group conveyed.

These differences between the two groups of children were due to one of the groups leveraging asymmetrical virtual immersion and perspectives, which is striking. On one hand, our findings suggest that working concurrently from the same perspective without the immersive experience afforded by the VR HMD, children would be more satisfied with their design and might even be more inventive with their design. Unbothered by usability constraints for the future user, one can focus on the overall originality or playfulness of design. Not feeling too critical about design and being playful may be essential for creativity. However, there is a fine line between being hypercritical vs. feeling free and creative. Therefore, if the primary goal of the design is to maximize inventiveness or creativity or if the project is at an early conceptual stage, utilizing virtual immersion and perspective-taking in the early ideation process might actually shift the focus too much towards the usability of design.

On the other hand, our findings suggest that if the primary goal of the design is to be user-centered, it may be beneficial to work with a virtual immersion to increase empathy for the user, even from an early stage of design. The introduction of virtual immersion in an SAR design environment such as our VR SandScape can invite children to "put themselves in the shoes" of the future user of their design while they build it. Furthermore, having asymmetrical access to virtual immersion (since there is only one VR HMD) among two collaborating children introduces a situation where both children are constantly put in the position to consider their design from both egocentric and allocentric perspectives since they cannot both be immersed at the same time.

Ultimately, our findings suggest that we, as design researchers, need to be sensitive to design goals and design stages and understand how virtual immersion affects how children look at their design and communicate their perspectives, either critically or agreeably. Having equal or asymmetric access to such design tools influences how children access different perspectives in their design process, ultimately affecting their attitudes towards the design activity and the final design outcome.

7. Future work

Our study showed that asymmetrical virtual immersion influenced middle school children's design processes, attitudes, and outcomes when partaking in collaborative design activities. In addition to middle schoolers, we conjecture how the same might apply to adults. While it is beyond the scope of this work, taking another's perspective and applying it to a creative process is a lifelong learning process. Further research with adult participants as well as joint adult–child collaborations leveraging VR HMDs may be beneficial.

Our setup employed one VR HMD with a SAR sandbox which allowed only one partner to be in VR. How might the turn-taking and design process be influenced if there were multiple VR HMDs that allowed for both partners to be immersed simultaneously? Would a setup that allowed equal, shared access to a virtual immersive environment invite children to work in distinctive phases of designing vs. navigating sequentially as our Non-HMD group did? Or would the immersive experience of noticing design improvement opportunities in VR still encourage the children with equal access to VR to voluntarily move between designing, navigating, and repairing to iterate on their design? The future study should investigate the interaction between symmetric access to virtual immersion and the iterative design process.

While this work focused on the increased empathy for the user brought out by experiencing scale differences through a maze design task, future work may also investigate VR as a lens for children to experience a variety of other perspectives (e.g., different abilities, limitations of resource, etc.) in their design process to investigate increased empathy in a variety of ways other than scale manipulation. With the development of age-appropriate VR HMDs permitting, a study with younger aged children investigating developmental trends of whether VR may increase their capacity for empathy in design work when compared to children who never used VR, may be beneficial.

In line with our findings that asymmetrical virtual immersion encourages children to engage in allocentric perspectives, we also call for more studies that examine the forms of collaboration developed by leveraging the tools in this study (i.e., a hybrid SAR sandbox and VR). Future studies should examine the design considerations of all types of VR experiences, be it HMD (with implicit VR navigation through head orientation sensing) or fixed shared displays (with explicit manual VR navigation), and how they afford or constrain feelings of empathy among school children. Given that children and youth are early adopters of VR, more work should be done to better understand what VR experiences mean to young people and how they make sense of the experience beyond the tool's intended use.

Finally, in the current online learning environment during the COVID-19 pandemic, where children are being asked (or required) to attend hybrid modes of instruction (some children or instructors may be geographically co-located while others are not), this work becomes imperative for highlighting how technology-mediated experiences could help support children's ability to access allocentric perspectives. As we ask children to learn in virtually co-located spaces that are physically distant, we must also carefully attend to the types of learning activities that the new digital reality could support. Future studies should investigate how children attend to and coordinate egocentric and allocentric perspectives through multiple digital screens in learning environments. This work contributes to an understanding of how to design technology that moves away from learning experiences based on individual singular perspectives and towards technologies that support collaborative learning experiences that leverage concurrent egocentric and allocentric perspectives. This research may be timely given that the pandemic has asked children to exist in learning spaces that demand various perspectives in multiple spaces.

8. Conclusion

We have presented our study with middle school students designing and building their original maze models using our VR SandScape system. The results of our study show that having asymmetric access to a virtual immersive environment encouraged pairs of children to take turns being a designer and a user. This turn-taking collaboration led to their shared maze design being constantly critiqued and repaired from both egocentric and allocentric perspectives, which in turn led the children to incorporate more user-accessible features such as wider paths and gentler slopes. Our findings indicate that children in the VR HMD group developed more user-attuned designs as they collaborated with and gained immediate feedback from their partners' embodied user experience in the virtual simulation. On the other hand, the children in the Non-HMD group without direct access to virtual immersion felt unconstrained by or did not consider the difference in scales they worked with and created more complex and playful mazes. While they did not significantly consider usability, they enjoyed engaging in world-making of their own whims, and were more immediately satisfied with their designs than the HMD group. We contribute our observation of VR as an enabling technology of such perspective shifts, from egocentric to more allocentric views, influencing both the processes and outcomes of the children's designs. However, we also argue that we need to be careful with how such perspective shifts can voluntarily shape the design activity's goal to be focused more on usability as opposed to an open and unhindered ideation process. We need to be sensitive to the design goal and stage and have the appropriate balance with awareness of how the tools we use focus our design activity as well as how they are being negotiated among collaborators. Our findings contribute to a greater understanding of how virtual immersion has a potentially unique role in supporting how children see and engage with their design.

Selection and participation of children

Sixteen children, seven girls and nine boys, at an urban middle school volunteered to participate in our study with their parents' permission from October 2019 to January 2020. All sixteen children knew each other as classmates and formed eight pairs of design collaborators. Four pairs were placed randomly into the HMD group and the other four into the non-HMD group.

It is important to note the age restrictions that come with current commercially available high-quality VR HMDs such as Oculus and HTC Vive: they are rated for users 13 years or older because HMDs are designed to be worn on adult-sized heads. While the HMDs come with adjustable straps, the display may appear blurry if the headset does not fit well. While brief exposure (e.g., under 20 minutes) to some blurriness should not be harmful (Bailey & Bailenson, 2017), effects from long-term usage are currently unknown. For safety reasons, and in adherence to manufacturer's guidelines, our study did not allow children under the age of 13to participate in the HMD experience.

While twelve of them were 13 years or older, four were age 12 at the time of recruitment and turned 13 during our study. We first distributed these four 12-year-old children between two groups to have equal age distribution. We then ensured that the two 12-year-old children in the VR HMD group waited until they turned 13 to use the HMD. The two 12-year-old children in the non-HMD group did not have access to an HMD. The rest of the children were paired based on their schedule availability and remained with the same partner throughout the project. While half of the children had a brief prior exposure to VR HMD (e.g., trying out a demo at a mall), none of the children had extensive experience using VR. The names used in this paper are pseudonyms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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