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Non-visual Virtual Reality: Considerations for the Pedagogical Design of Embodied Mathematical Experiences for Visually Impaired Children

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ABSTRACT: Digital developments that foreground the sensory body and movement interaction offer new ways of engaging with mathematical ideas. Theories of embodied cognition argue for the important role of sensorimotor interaction in underpinning cognition. For visually impaired children this is particularly promising, since it provides opportunities for grounding mathematical ideas in bodily experience. The use of iVR technologies for visually impaired children is not immediately evident, given the central role of vision in immersive virtual worlds. This paper presents an iterative, design-based case study with visually impaired children to inform the pedagogical design of embodied learning experiences in iVR. Drawing from embodied pedagogy, it explores the process of implementing a classroom-based non-visual VR experience, designed to give visually impaired children an embodied experience of position in terms of Cartesian co-ordinates as they move around a virtual space. Video recordings of interaction combined with feedback from teachers and children contribute to knowledge of iVR learning applications in formal settings by discerning three types of pedagogical practices: creation of a performance space introduction of performative actions and action connected diverse perspectives.

Keywords: Virtual Reality, Visually impaired children, Embodied learning, Cartesian coordinates

1. Introduction

Embodied learning is increasingly important in shaping how to teach mathematics, given evidence suggesting that mathematical knowledge is embodied (Alibali & Nathan, 2012). Embodied learning has particular potential for teaching visually impaired (VI) students, since it engages multiple senses including proprioception, bodily action, touch and hearing, rather than focusing primarily on visual resources. Immersive Virtual Reality (iVR) has the potential to foster embodied forms of teaching and learning mathematics through whole body sensorimotor interaction (e.g., Price et al., 2017), yet the benefits for VI children is not immediately evident, given the central role of vision in immersive virtual worlds. A significant body of work has explored technical application of tactile and multimodal feedback in VR for VI particularly transforming spatial information to auditory cues to support navigation (Cobb & Sharkey, 2007). However, the educational application of iVR with VI children remains under-researched.

Compared to their "seeing" counterparts VI children typically fall behind in science and mathematics by one to three years (Quek et al., 2006). Learning about Cartesian coordinates is important for developing spatial understanding - a challenging competence in everyday life for VI, and considered a fundamental concept for mathematics and science (Knuth, 2000). VR applications lend themselves to spatial concepts like Cartesian coordinates through their potential to support embodied interaction with the learning environment (Johnson-Glenberg, 2018). Yet little work has examined the use of iVR to support VI children's embodied learning in school settings. Embodied learning has important implications not only for the design of digital environments, but also for the pedagogical design surrounding implementation in the classroom. If the learning of mathematics is shaped by our embodied physical and sensory experience, then the particular physical and sensory experiences we design and how they are pedagogically facilitated are significant in shaping mathematical understanding. iVR has important implications in terms of disrupting existing classroom practices, given different physical space and set up requirements and pedagogical orchestration. The use of iVR with VI children in a school setting, poses additional challenges. While studies referring to iVR in education ground their design and implementation in learning theories like embodied learning (Johnson-Glenberg, 2018) and integrating learning content (Dalgarno & Lee, 2010; Hanson & Shelton, 2008), less attention is given to implementation in classroom contexts, and explicit reference to pedagogy is missing (Southgate, 2020). This is of particular importance given that technology alone does not teach: "it is educational practices that determine how well students learn, and technology is not a process but a tool through which educational practices are mediated" (Rappaport cited in Niederhauser, 2013, p. 249).

Drawing on this perspective our research question asks: What educational practices can support VI children to engage with embodied exploration of mathematical concepts through the use of iVR in the classroom? Thus, our study focuses on informing pedagogical practices that frame the use of iVR to support embodied learning through examining student-facilitator interaction in the iVR environment. We report the iterative development of a pedagogical design to support VI children's learning about Cartesian coordinates with a purposely designed iVR environment (the Cartesian Garden). The Cartesian Garden is made accessible for VI children by focusing on proprioception and bodily movement in space linked to sound, rather than primarily relying on visuals. Through qualitative analysis of interaction and interview data we explore the way VI children used multisensory affordances of the iVR environment for meaning generation to identify pedagogical approaches that enable children to effectively engage with mathematical ideas without visual feedback. We discuss these findings drawing on notions of embodied pedagogy (Nguyen & Larson, 2015) to outline key pedagogical strategies for implementing and supporting a VR embodied learning experience for VI children in the school classroom.

2. Background

2.1. Embodied learning and mathematics

Lakoff and Nunez (2000) assert that mathematical knowledge is understood through the body situated in the physical environment. Evidence for the embodied basis of mathematics has been shown in research with children and teachers (e.g., Alibali & Nathan, 2012; Lakoff & Núñez, 2000), and the critical role of action in underpinning important sensorimotor representations that can be used later in reasoning (e.g., Abrahamson & Sánchez-García, 2016; Nemirovsky et al., 2012). Embodied learning has important implications for the design of technology and the orchestration of the related learning experiences.

Cartesian coordinates have typically been studied with older students who are not visually impaired (e.g., Boyce & Barnes, 2010; Knuth, 2000). The concept of the Cartesian plane is considered critical for spatial perception, spatial relations and navigation, and in understanding mathematical concepts like functions (Knuth, 2000). Cartesian coordinates offer a way of using the environment as reference for navigation and particularly for undifferentiated and large scale environments (e.g., grids on city maps) (Dokic & Pacherie, 2006). For VI children in particular, embodied engagement through patterns of movement have been acknowledged as an instrument for developing spatial perception and integrating spatial information (Jones, 1975). Studies on spatial perception of the blind offer different theories on the role of vision in spatial understanding. While this debate is beyond the scope of this paper, these theories show that the different modalities used for the exploration of space shape the way spatial information is structured. In this paper iVR is designed to support embodied exploration of Cartesian coordinates through sound and sensorimotor interaction with the learning environment.

2.2. Immersive virtual reality and embodied pedagogy

iVR enables users to interact in worlds that simulate aspects or situations of reality that offer new opportunities for education. Most educational VR application studies involve adults at university, college or training contexts (Freina & Ott, 2015). Fewer studies involve middle school students or elementary students, partly due to insufficient knowledge of potential health (e.g., dizziness) and ethical issues involving young children's use of Head Mounted Displays (HMD)), although 5-10 minutes incremental use for young children is reported to be unproblematic (Aubrey et al., 2018).

For the visually impaired, iVR offers suitable navigation training, as it provides a controlled, customizable and safe environment for this purpose. Research in this domain is limited, involving mainly teenagers or adults and focuses on the technical and usability aspects (see Allain et al., 2015). Other research using non-immersive VR with VI children explores the role of sound in mental structure construction and spatial imagery of VI children (Lányi et al., 2006; Sanchez & Lumbreras, 2000). While these studies offer valuable insights into conceptualizations of space by VI children, non-immersive VR studies do not focus on full-body exploration of the environment: an important aspect of spatial thinking. Furthermore, little research has explored the use of iVR in school contexts rather than lab settings with typically developing or VI children. As a result there is lack a focus on pedagogy (Southgate, 2020). While early attempts looked at ways of integrating content (Dalgarno & Lee, 2010; Hanson & Shelton, 2008), more recent studies include introducing iVR technologies to learners and teachers, connection to the curriculum, types of feedback and integration of collaboration problem solving activities (Southgate, 2020; Johnson-Glenberg, 2018). Johnson-Glenberg (2018) proposes guidelines with specific reference to how gestures and body metaphor can be integrated into pedagogical design. However, challenges of implementing iVR in classroom settings and developing appropriate pedagogical strategies has not been explored.

iVR technologies vary in terms of equipment and forms of interaction they enable. Deciding on which type of VR to use has important implications for classroom practice, from cost requirements to physical space, set up, student involvement and interaction, and teaching strategies. HMDs for iVR isolate the user from the physical environment and require space of at least 3X3 meters. The disruptive nature of iVR also poses critical pedagogical implementation challenges in classroom settings, which have not been previously addressed. This paper explores the pedagogical implementation of iVR into the classroom with VI children, specifically attending to the embodied nature of interaction to identify key pedagogical requirements drawing on notions of embodied pedagogy.

Embodied pedagogy focuses on how to engage the body and space in learning (Nguyen & Larson, 2015). It is defined "as learning that joins body and mind in a physical and mental act of knowledge construction. This union entails thoughtful awareness of body, space, and social context" (Nguyen & Larson, 2015, p. 332). In embodied pedagogy, knowledge construction takes place in a performance space which prescribes spatial arrangements not only of objects but also of body position, orientation, movement and action. The relationship between body and mind is expanded to include the material situation of the performance space and the human (i.e., teacher- student, student -student) interdependencies (Southgate & Smith, 2016). Meaning construction in embodied pedagogy involves a cyclical process of mindful action and reflection which shapes the learner and the space and spatial arrangements where action takes place. Action is not simply situated in the environment. Instead people and the environment, transform and shape each other through ongoing transactions (Sund et al., 2019). While these transactions are instrumental for progress, introducing diverse perspectives in the action–reflection cycle can instill the physical in the reflective and the reflective in the physical in unexpected ways, resulting in new modes of learning (Southgate & Smith, 2016). iVR technology foregrounds space and physical action in the teaching and learning process, thus demanding engagement with embodied pedagogy. Our study draws on principles of embodied pedagogy to identify particular considerations that can inform the implementation of iVR in the VI classroom to effectively structure an embodied learning experience.

3. The Cartesian garden environment

The environment uses HTC Vive to create a VR experience space measuring 5mx5m, consisting of a floor-based virtual grid in the form of a virtual garden, with flowers at each of the coordinates. X and y-axes run from 0-5 in the standard layout for Cartesian coordinates for children. Children walk along the axes to find and collect target flowers at specified coordinates. For VI children sounds and vibration on the controller provide feedback that maps movement to coordinates. As the child moves around the grid, they hear sounds from a set of speakers that indicate their position in relation to the grid lines. A controller attached to the child's waist using a belt vibrates when the child encounters a cross point. To find out their exact position (in relation to the coordinates) the child presses the controller trigger and the position is defined using sound.

Sounds: Sounds convey directional and mathematical properties: movement along the x-axis is indicated by flute notes and movement along the y-axis is indicated by violin notes. As the child walks along the x-axis they hear only flute notes, when they walk along the y-axis they hear only violin notes. The directional properties of the sound involve embodied action: the further the child moves from the origin on one axis the more notes they hear. In order to hear a combination of notes they need to move within the middle of the garden (within the quadrant). Thus, position (3, 2) is expressed by three flute notes, followed by two violin notes. Two different instruments played sequentially and mapped to the two axes aims to demonstrate that coordinates are pairs of numbers describing distance in orthogonal directions. An ambient sound indicates that the child is on a grid line, but stops when the child is off the line, a "ding" sounds when they reach a cross point, and white noise is heard when they are on point 0 (1,0 would be one flute note followed by a white noise).

Screen: A 2D computer screen depicts the garden as a grid of flowers with the child's position and orientation indicated by a red triangle (Figure 1). In this study the screen was used by researchers in order to identify technical problems, like lack of feedback.

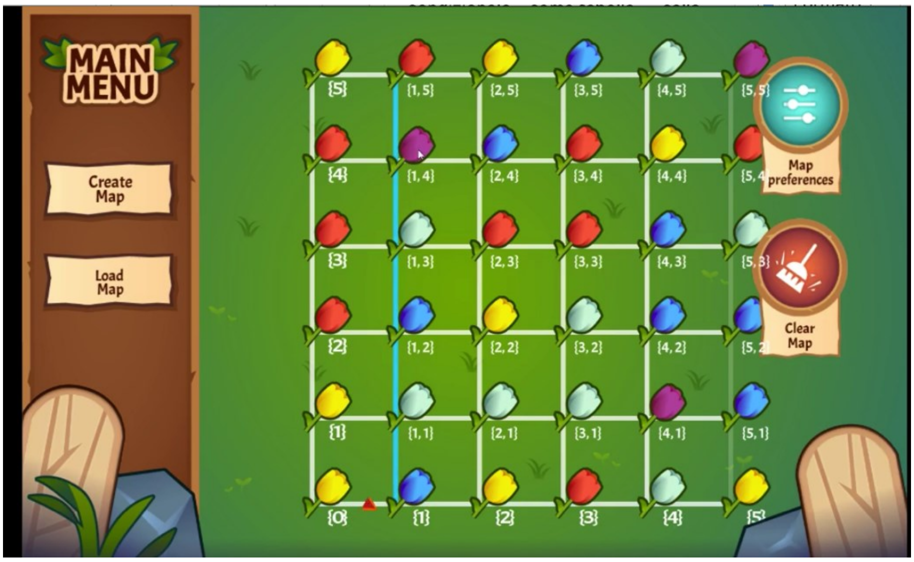

Figure 1. The computer screen shows the garden. The red triangle near (1,0) is the position of the player

VR Headset: When wearing the VR headset children with usable vision are immersed in a garden of flowers. However, for VI children relying on other modalities the VR headset was not used, position being conveyed by sound and vibration as described above.

4. Methodological approach

An iterative design-based research approach was taken to develop an effective pedagogical design around the VR experience with VI children, drawing on researcher and teacher facilitation of child interaction. Design based research aims to improve educational practice through iterative design, development and deployment of educational activities in real world settings, developed through researcher-practitioner collaboration, with a view to generating design guidelines (Wang & Hannafin, 2005). In this paper we report on a two-phase study focusing on the iterative design of the pedagogical strategies needed to effectively implement a iVR learning experience for VI children into the school classroom. The study drew on children's interaction, researcher-teacher facilitation, teacher and child interviews. Informed consent to participate was obtained from children and their parents. Methods for each phase are detailed under each study.

5. Phase 1

Phase 1 aimed to identify a set of pedagogical designs to be implemented and evaluated in Phase 2. Phase 1 was conducted with one blind child aged 8 [C2]. The child interacted with the iVR experience with the help of a researcher and his teacher for one hour. This was followed by an informal interview with the child about his experience, and with the teacher about pedagogical feedback. A second researcher video recorded the session and took notes while a third operated the technology. The child was encouraged to comment on his experience and was told that this would help us identify if something was not clear or difficult to understand, to then improve the experience. Data comprised video recording of interaction and observation notes, including the discussion with teacher and child. Researcher reflection on these data led to identifying key pedagogical design issues around the VR experience. Three key aspects emerged that informed development of the pedagogical design for Phase 2: space, body movement and concept/activity framing.

5.1. Space: Physical and virtual

Physical Space: played a critical role as the way children moved in the space was essential for fostering meaningful embodied engagement with Cartesian coordinates. The research sessions took place in a dedicated classroom with free space of 5X5 for the VR overlay, within which children could freely move. This room was unfamiliar to the children: it was the science classroom which children had visited only twice, and the furniture had to be rearranged to meet requirements for the VR set up. Thus, we needed to orientate them, explain that they would only be moving in the free space between the door and the window, and assure them that the researcher would be next to them to guide and make sure they did not bump into anything during the interaction.

VR Interaction Space: Aligning the VR overlay in the physical space and 2D representation was found to be critical since the researcher and teacher needed to easily identify where the child was in the virtual garden, to guide them appropriately and ensure they received feedback on their position. Sticky tape was used to mark key elements of the Cartesian plane (i.e., axes, origin, and distance between flowers on the x and y axes) on the physical floor space. Researchers used floor markings to guide the child to refine his movement appropriately. However, C2 required more support within the central parts of the quadrant to effectively receive sound and haptic feedback. The floor marking was thus extended to include the cross point positions with an emphasis on the position of the child's feet from the VR feed (green cross) and the position of the controller (blue line), which were not directly aligned because the controller sits fractionally in front of the feet (Figure 2). This alignment was critical in facilitating the transactional relation between children (moving in space), the researcher-teacher (supporting children to refine their movement) and the iVR environment (offering feedback).

Figure 2. The physical space marked out to facilitate VI children's movement in the VR space, aligned to the grid

5.2. Movement

Phase 1 revealed key difficulties for C2 in mapping their bodily movement to the grid. Moving through the Cartesian Garden was not only dependent on the child's understanding of their current position and the position they were aiming for, but also their bodily orientation with respect to the axes. For VI children there are few external cues to inform them in which direction they are facing. The iVR experience gives feedback on position but not orientation. While C2 made a quarter turn with his body every time he changed from moving in the x direction to moving in the y direction, it was not always clear which direction to turn. In addition, it was not always easy for him to 'sense' when he had achieved a precise 90-degree turn. To avoid disorientation the researcher had to specifically state the direction the child was facing. As the session progressed C2 adopted a fixed orientation with his body always facing in the y direction (as if looking at a graph on a piece of paper) and stepping sideways along the x-axis. In this way, the child used their body as an anchor for orientation. Following teacher advice, the VI children were led by the hand from the front, guiding them so that the researcher steps into the unknown first, to help children feel safe, yet allow them to follow at their own pace.

5.3. Concept/activity framing

Phase 1 revealed the need to familiarise VI children with the notion of grids. C2 was not easily able to make connections between his whole-body experience and the external layout of the garden. During interaction it became apparent that he was not familiar with the concept of a grid. The teacher intervened and introduced a tactile grid to help explain the idea to the child:

Now you find those squares, if you follow that line all the way up (she guides his hands) and there's another line that goes across (she guides his hands) So when we are talking about the garden, the garden kind of looks like this. So, this garden that you are walking around on.

Non-VI children using a headset could see the grid and explore ways of moving related to sound and visuals. For VI children reduced access to the visual representation, demands alternative ways of introducing the key grid structure and related movement. By combining the tactile grid and the fixed body orientation strategy C2 was better able to negotiate the space and pay attention to how the sounds related to his location and could guide his next steps.

Phase 1 also highlighted challenges in explaining the garden and linking mathematical terminology. Although we introduced axes as lines following a particular direction and encouraged C2 to explore how the sound changed as he moved along the axis, he had difficulty identifying the two different sets of sounds mapped. This highlighted the need to develop a strategy that clearly explained the mapping of sounds to two different paths.

5.4. Adaptations for Phase 2

Based on Phase 1 the following changes were made to the experience structure and pedagogical process:
Awareness of Physical Space: Due to children's unfamiliarity with the physical space we identified the room they were in and described the layout to provide the necessary information for children to locate themselves in space.

VR Interaction Space: The physical space was marked with paper tape to enable researchers to facilitate interaction with the VR experience reducing the difficulties in finding the exact location where the system provided positional feedback to the children.

Tactile grid: An improved tactile grid (Figure 3) was included to enable children to explore the layout of the grid and spatial relations between different positions before they started moving in the garden space.

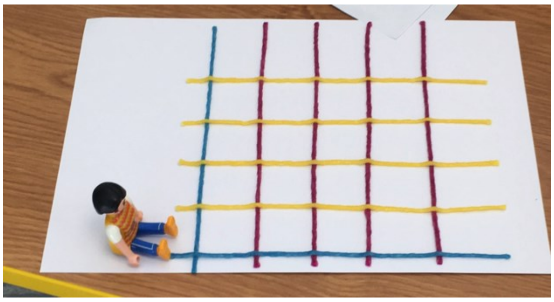

Figure 3. The tactile grid made from wax string pressed on to an A4 sheet of card, and a playmobile figure

After their interaction in the iVR space, children were presented with a playmobile figure and asked to move it on the tactile grid to specific coordinates (Figure 3), in order to explore any learning transfer from the physical VR space to a more abstract 2D space.

Guiding: The researcher guided children by the hand from the front to ensure that they remained within the iVR experience space. However, to avoid implicitly leading the child to the correct answer the researcher kept some distance between them, allowing the child to move towards the direction indicated by the child.

Fixed Body Orientation: The children were advised to stand facing towards the y-axis and take a combination of side-steps and forward or backward steps to navigate the grid, as follows: "In this garden you have to walk in a specific way: first you have to move sideways as many squares as the flute player tells you, and then you have to move forward as many squares as the violin player says."

Violin and Flute Player: To help children link the different sounds to location along the axes we explained that a flute player was sitting at the end of one path (x-axis) and a violin player at the end of the other (y-axis), and as they walk towards the musician, they will hear more notes. We renamed the origin to "garden gate" and spoke about position in terms of number of flute and violin notes, rather than coordinates at this stage.

Magic Flowers: To better integrate the flowers and give a more play-like quality to the experience, we introduced the idea of a magic flower: two flutes, three violins, which the children had to find. If the children found the magic- flower they could choose the magic powers it would give them.

6. Phase 2

Phase 2 implemented the changes in the pedagogical design outlined above and explored how these appropriations fostered embodied engagement with Cartesian coordinates mediated by the iVR experience.

6.1. Participants

Seven visually impaired children (2 girls and 5 boys) aged between 8 and 11 years took part, including the child from Phase 1. The teacher classified the children according to their visual ability into two main groups: (a) children who could see shapes and/or enlarged prints if brought close to their face and could read extremely large lettering. These children moved around without the need of a cane (1 girl and 4 boys); (b) children who were blind and needed a cane to move (one boy and one girl). Within these two broad categories there were differentiations including children who had lost their sight after birth and children who were born blind or with visual impairment. This differentiation is important since children who are born visually impaired or blind have very poor or no visual representations, impacting how they understand space and instructions. Given the range of visual impairments, ages and educational needs, each child took part in the experience individually.

6.2. iVR Interaction sessions

The researchers visited the classroom prior to the research sessions, introduced themselves, explained the activities and the technology. Children had the opportunity to touch and explore the controllers and belt in order to familiarise themselves with the equipment, enabling children to demystify the technologies and reduce potential anxiety with unknown things (people, tasks, technologies). Each session lasted approximately 45-50 minutes. Each child was accompanied by the teacher, who advocated on behalf of the child in case they became tired or needed to stop. The sessions were structured in three parts: a short informal interview to identify children's experience with computer games, and knowledge of grids and coordinates; introduction to the Cartesian plane through exploration of a tactile grid (Figure 3); a short discussion about their experience and completion of tactile grid tasks. One researcher took the role of facilitator, a second took notes and a third operated the technology and video camera. Most participants had not learned about grids before.

6.3. Data collected and analytical approach

Data included video recordings of children's interaction and pre and post interaction discussions, screen capture of the 2D representation of children's movement, and researcher reflective notes of the sessions, including interactions with the teacher. Video data transcription attended to movement in relation to the physical space, the virtual grid and technology feedback, and verbal interactions. The analysis follows an inductive (looking for emerging themes) and deductive (informed by concepts of embodied pedagogy) process to derive key implications for the development of the pedagogical design towards embodied exploration of the Cartesian Plane. The following section presents the key findings used as a basis to evaluate our pedagogical design. While each section offers insights from all participants, key illustrative examples are drawn from four cases.

7. Findings and discussion

Phase 2 enabled explored the role of the implemented pedagogical strategies in supporting VI students' embodied exploration of mathematics. The findings show how bodily movement and positioning can effectively foster VI children's engagement with the Cartesian plane, and the role that sound and researcher facilitation played in this process. These findings are discussed within the frame of embodied pedagogy (Nguyen & Larson, 2015). The iVR design itself creates a performative space. Our findings illustrate how populating this space with performative actions and introducing diverse perspectives (Nguyen & Larson, 2015) facilitated mindful action i.e., embodied action and reflection.

7.1. Performance space

The Cartesian Garden creates a "performance space" through: (a) the physical space allowing for whole body movement; (b) the virtual overlay that provides a narrative for interaction; and (c) the relationship between body and physical-virtual space. Phase 1 analysis showed that spatial arrangements enabling children to know the relative positioning and orientation of their bodies was critical for interaction in the iVR environment. These spatial arrangements formed the basis of performative actions that supported embodied learning interactions.

The narrative of the magic garden provided meaning to the task and raised students' interest through the introduction of make-believe elements (garden of flowers) and set the scene for identifying objects, bodies, relations and actions in the specific space (i.e., collecting flowers from a regulated garden layout). The pedagogical appropriations included the introduction of a set of performative actions which embodied key aspects of the Cartesian Plane (axes, orientation, order of coordinates), aiming to facilitate embodied interaction with the mathematical concepts.

7.2. Performative actions

Embodied pedagogy acknowledges performative thinking as an embodied process linked mainly to role play (Nguyen & Larson, 2015). In our study, performative thinking is connected to specific appropriations of the learning environment, that allow performative actions or ways of moving in space which embody specific mathematical ideas. These performative actions took the following forms:

7.2.1. Musical paths: Embodying properties of the Cartesian plane

In the iVR environment, walking along the axes was linked to the sound of different instruments. The task descriptions introduced a narrative involving two musicians sitting at the end of each path (axis). This added directional and distance properties to the musical metaphor: the closer the child moved towards the musician the more notes they could hear. The sounds thus shaped a set of performative actions, which in this case involved ways of moving in space. It is worth noting that these performative actions, which combine movement with sound constitute a common practice in the sociocultural context of VI children.

When children were introduced to the garden they began at the origin (0,0 or the garden gate) with their body oriented to face the y-axis direction. In Phase 2 children were shown the path to the flute player (x-axis) first, and were told to take side steps along the axis. As they stepped along the x-axis they experienced the flute sounds at each cross point, the number of flute notes increasing as they went further along the path. They were then taken back to the "garden gate" and stepped forward along the y axis, experiencing the path to the violinist, again hearing an increased number of violin notes at each point. Once they reached 4 violin notes (0,4) they were asked "if I wanted to hear flute notes as well as violin notes which way should I step?" This was a transition point where they had to go from perceiving flute and violin (x and y coordinates) as describing the paths of each music player (axes) to perceiving them as locations requiring movement in a direction parallel to one axis. Few children were able to immediately work out that they needed to step sideways into the middle of the garden to hear the flute as well as the violin. One child (C3), who was partially sighted, described how she did map this use of sounds:

"*Each path has its own instrument, for example that's the violin and that's the flute. So if I'm at the top of the violin path I just have to go here [she indicates walking parallel to the x axis at y = 4] I don't have to go back here to the actual path because the path is invisible on the floor but it's still the same way as the violin line goes – the same way as the flute line [correcting herself] - So I just go the same way as the flute line rather than going back down, otherwise I won't get the flower.*"

Children who struggled with this initially only walked along either of the paths they had been shown (x and y axis), requiring encouragement to explore the middle space. Even after being shown that there were positions in the middle of the garden, with both flute and violin notes, some did not immediately move into this space. For example, although C5 had already explored the middle of the garden, he still needed prompting to step off the axes to find coordinates in the middle of the quadrant.

[C5 is looking for two flutes and four violins. C5 has identified that he needs to move right to get the flutes.]
…
R1: So we have two flutes, now we need four violins which way do we go?
[C5 moves back towards the origin to start from there up the y axis. C5 gradually moves up the y-axis to (0,4).]
R1: How many violins do we have?
C5: Four
R1: But how many flutes do we need?
C5: Two
R1: Where are we going to get them?
[C5 gestures back to the origin]
R1: If we move along the first path, we will only have the flutes and no violins. But we need 2 flutes and 4 violins so...

C5: This way [gestures towards the middle of the garden]

This movement pattern enabled children to listen to the sounds sequentially: first they heard one sound, moved back to the origin and then in the other direction to hear the second sound. This pattern of moving towards one music player, then return to the origin and walk on the other axis towards the second instrument player, served as an embodied manifestation of children's thinking, allowing for reflection and teacher intervention. Later when C5 was asked to take the playmobile figure to position (3,2) on the grid, he also moved the figure to (3,0) first, back to the origin and then to (0,2). While children were prompted to explore the middle of the garden to hear both sounds, four were able to do this effectively. This suggests the need for additional strategies to help them conceptualise the paths that run parallel to the axes.

7.2.2. Orientation and movement: Embodying properties of Cartesian coordinates

Children were guided to adopt a fixed body orientation facing the y-axis, to step sideways to move along the x-axis and forward to move along the y-axis. This unorthodox way of "walking in space" employs the idea of congruence between embodied action and concept (Johnson-Glenberg, 2018) to integrate key properties of Cartesian coordinates involving specific rules for interaction (i.e., x then y), and orientational alignment with other representations e.g., tactile grid. Children were asked to find a magic flower positionally described as 3 flute 4 violin (coordinates (3,4)). Some children started from the origin (0,0) walking sideways along the x-axis then moving forward along the y-axis (Figure 4), others adopted the pattern: x, origin, then y, outlined above (7.2.1). Children used the controllers to get sound feedback about their position. The extract below demonstrates how C4 applied the sideways first then forward pattern of movement in combination with sound feedback in order to successfully find the magic flower using coordinates.

R3: Magic flower at three flute, three violin.
...
[C4 takes small step forwards, hears ding, presses trigger, two flutes.]
R1: How many were there before?
C4: Two
...
[C4 takes big step to right then little step forward, hears ding, presses trigger, three flutes]
R1: Great, so we've got three flute and [want] three violins.
R2: So, where do you go from there to get three violins?
...
[C4 takes a big step forwards, ding, presses trigger, three flute, one violin. Takes another big step forwards, ding, presses trigger, three flute two violin. Takes another big step forward, ding, presses trigger, 3 flutes, 3 violins]

In this process C4 used the controller to get sound-based positional feedback and adjusted his movement accordingly (i.e., calculated the direction to move and how many steps to take). All children used the feedback offered by the controllers but two out of the seven children waited for researcher feedback rather than interpreting feedback from the controllers. The researchers prompted them to listen to the feedback carefully, verbalise what they were hearing, and describe how they should move. In the iVR environment, feedback facilitates the mindful action–reflection cycle of embodied pedagogy: the sound feedback helps the child to become aware of their position in the performance space, to reflect on this position and decide their next action. The combination of feedback with introduction of the specific pattern of movement proved instrumental in supporting embodied learning for VI in the iVR experience.

7.2.3. Guidance: Embodied instruction

The interaction between the teacher/researcher and student generated a set of performative actions specific to the iVR space. All 7 children needed guidance to remain within the performative space given the small unbounded space aligned to VR. The teachers-researchers adopted specific ways of guiding the children, informed by the sociocultural context of the students and school. This involved leading them by the hand from the front, but letting the child indicate their chosen direction of movement, or giving directional hints through leading when necessary. In this way guidance took the form of embodied instruction and intervention.

7.3. Diverse perspectives: Multisensory experiences

Diverse perspectives were introduced by supporting different and interconnected sensory modalities. Sound feedback was connected and responsive to movement designed to enable reflection informing mindful action. Further, different activities on the Cartesian Plane were introduced, placing the body in different points of view of the same concept, and creating embodied links across representations (Nguyen & Larson, 2015). Specifically, the iVR environment offered a space where the child's body became part of the grid, facilitating ego-centric exploration; the tactile grid used before the activity enabled children to haptically gain an introductory overview (similar to visually perceiving a paper-based grid) of the Cartesian plane as a space consisting of squares with intersections as key points for describing position; in the post interaction discussion, the grid offered an allocentric perspective when children were asked to move a playmobile figure into a position described by coordinates.

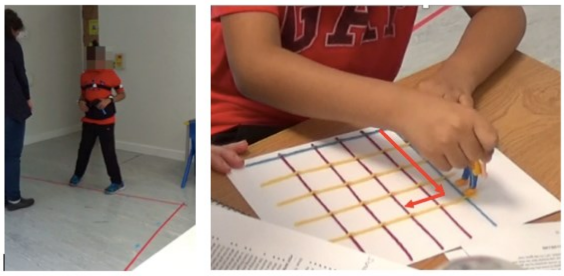

Figure 4. Patterns of movement transferred from the 3D space to the 2D representation of the Cartesian plane

In this study performative actions played a role in transcending different perspectives and supporting transfer of knowledge from one representation to the other. In the post interaction discussion all children were able to transfer their knowledge from the physical space to the 2D haptic grid representation, using the same moving pattern as a common referent between the two spaces. Four children were able to find the correct position in the Cartesian plane. Three children using on the haptic grid their patterns of movement in space, focused only on the two axes (x,y) without considering coordinates in the middle of the grid (see section 7.2.1). The powerful role of patterns of movement is illustrated in the post interaction discussion with C4. The marking of the trajectory on Figure 4 shows that C4 moved first sideways along the y-axis (rather than sideways along the x-axis), allocating the first coordinate to the y instead of x-axis. The original orientation of the playmobile figure was changed by the child - during random play - to face towards the x-axis, thus influencing the direction of movement. This finding is interesting, if we consider previous research with typically developing children (8-9 years old) which demonstrated that this transition from enactment in the physical space to using the Cartesian plane on paper was challenging (Price et al., 2020).

7.4. Child reflections

The post interaction discussion involved the evaluation of learning through the use of the tactile grid, which was mentioned in the sections above, but also focused on exploring children's perception of the experience, and their evaluation of key functionalities (like sound feedback). While all children found the experience interesting and engaging, this can be attributed to factors like the novelty of technology, deviation from school routine etc. Further, children reflected on key aspects of the experience like the sound feedback. The majority of the children mentioned some difficulty in distinguishing the two sounds related to the x and y axes. This technical aspect having also conceptual implications as shown in the sections above, demonstrated the need for refining the sound feedback.

8. Conclusion: Pedagogical appropriation of iVR for VI

This paper shows the importance of developing appropriate embodied pedagogical designs to support effective integration of iVR in school settings for VI children. Through an iterative design process, our study offers insights into the prerequisites for implementation of iVR in the classroom and embodied pedagogical appropriations to support VI children to explore the concept of cartesian coordinates.

8.1. Prerequisites for classroom implementation

iVR disrupts existing school practices, calling for requirement specifications to implement the Cartesian Garden experience. Firstly, our study revealed the need for specific spatial arrangements and for appropriate physical space devoted to the iVR activity. Identifying specific space to deploy full tracking iVR systems highlights the spatial constraints of schools built for an industrial era (Southgate et al., 2019). Secondly, orchestration of the experience allows one child per session due to space requirements and VR features which foster individual interaction. In addition, at least one teacher per session is needed to facilitate the activity and provide appropriate support for the student, and potentially two adults with one to monitor/manage the technology, since iVR requires constant surveillance (Southgate et al., 2019). While individual sessions with children in VI schools are not unusual, iVR currently has a considerable financial cost and requires many human resources. These observations are relevant not only to educational practitioners but also technology designers.

8.2. Pedagogical appropriations of iVR to support embodied learning

Our study, framed by embodied pedagogy, enriches existing recommendations specifically addressing the use of iVR in classroom settings (Johnson-Glenberg, 2018; Southgate, 2020) by discerning the role of performance space, diverse perspectives and performative actions as key elements in supporting embodied learning. Table 1 presents a summary of pedagogical appropriations their connection to concepts of embodied pedagogy and their pedagogical aim.

Table 1. Appropriations of iVR to support embodied pedagogy of mathematics learning

Embodied pedagogy	Appropriations	Function
Creating a performance space	Marking the floor to map the physical to the virtual to support adult facilitation	Facilitate the transactional relation between teacher-researcher, student, space
	Orientation alignment between computer screen and physical space.	Facilitate the transactional relation between teacher-researcher, student, space
	Introducing narrative or make-believe elements (magic flower)	Make the task meaningful and interesting for the children, introduce performative thinking
Performative actions	Familiarisation with performative space (verbal descriptions of space); Guidance strategies (from the front); Interaction strategies (moving/ using the controller to get feedback)	Facilitate the transactional relation between teacher-researcher, student and the environment
	Fixed body orientation mapped to axes travelling in orthogonal directions. Specific movement patterns: step sideways (along x axis) followed by forwards (along y axis) Musical paths metaphor to map to axes, providing information relating to direction, distance and position	Integration of key mathematical concepts in embodied actions
Diverse perspectives	Connect different perspectives: allocentric (haptic grid with playmobil figure) & body-centric perspectives (iVR through enacting position) connected with the same performative actions (i.e., fixed orientation and movement pattern) applied in both.	Support students to use performative actions as an embodied means to establish connections between different representations.

The appropriations above involve iVR designed for open embodied interactive exploration of mathematics. Drawing from embodied pedagogy our interventions fall into three key categories: performative space, performative actions and action connected diverse perspectives. Performance space includes the objects, persons, relations and their roles. In our intervention we populated the performance space with a narrative giving meaning to objects, persons and space, and with anchors (marks on the floor or orientation of the screen) that facilitated interactions between children, teacher-researcher and space. The anchors were implemented to complement the feedback provided by the iVR experience, with key additional information. Our study brings the concept of performative actions into educational practices. These are prescribed actions in the environment (objects, relations, people, space), which when enacted embody elements of the concepts under exploration (i.e., action congruence, Johnson-Glenberg, 2018). Student modifications of some of these movements demonstrated how they embodied the concepts of Cartesian coordinates, sometimes manifesting misunderstandings. Diverse perspectives implemented through role-play or through the use of different representations is an important aspect of pedagogy. Our intervention demonstrated how the use of resources, which allow children to implement the same performative actions across different representations, has the potential to support transfer of knowledge. While some of these appropriations could be integrated into the iVR design (e.g., movement patterns), a focus on performative actions, performance space and action connected to diverse perspectives can also inform teacher interventions and pedagogical design around the use of iVR.

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