

Perceiving Space Through Movement: Blind and Visually Impaired Learners' Spatial Explorations and Imaginations with Haptic Technologies in STEM Education Co-Design

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Abstract

Current math and science education tools have some limitations in their capacity to offer blind and low vision (BLV) learners equitable access to spatial information and opportunities for spatial reasoning. We explore haptic technologies as a toolkit to address this limitation through TeleTangibles: a “digital twin” reconfigurable haptics sensing/actuating toolkit for inclusive, dynamic, and collaborative math and science learning. The present paper analyzes data from a first co-design round exploring prospective TeleTangibles haptic interactions with BLV youth. Our preliminary results reveal the intra- and interpersonal affordances of haptic technologies for teaching and learning complex spatial concepts in math and science, including haptic experiences of spatial concepts and negotiating haptic interpersonal agency. As embodied theories of cognition underscore the interrelations of action, perception, and cognition, haptic technologies offer a promising tool to leverage the embodied epistemic practices of sensory-marginalized students to design more equitable learning technologies.

1. Objectives

Present instructional media for supporting middle school BLV learners of math and science include tactile graphics, braille textbooks, description, and text-to-speech. These approaches primarily invite engagement through the auditory and tactile modalities, using the semiotic modes of language, graphical representations, and braille. Prior work has highlighted the limitations of such approaches for offering BLV learners equitable experiences (Abrahamson et al., 2019). In particular, limitations have been identified in teaching spatial arrangements (Bell & Silverman, 2019), including 2-dimensional representations to convey order, positions, directions, and boundaries (Jitngernmadan et al., 2017) and 3-dimensional models (Hayes & Proulx, 2024). More broadly, researchers have implicated limitations in current offerings for BLV learners to develop spatial reasoning (Bell & Silverman, 2019). In parallel, informed by the embodiment turn in the cognitive and learning sciences (Alibali & Nathan, 2018, Shapiro & Stolz, 2019), recent work has shown promising results for the impact of haptic interactions on Science, Technology, Engineering, and Math (STEM) learning for sighted learners (Beier, & Rau, 2023; Crandall & Karadoğan, 2021; Price et al., 2021; Tang et al., 2025). Towards expanding haptic access to STEM concepts, the [Funder]-funded TeleTangibles design-based research project is investigating innovative technologies for leveraging the haptic modality in the inclusive teaching of STEM domains featuring dense, dynamic, and complex spatial concepts, such as electromagnetic radiation in science as well as geometry and functions in mathematics.

2. Theoretical Framework

Recent developments in understanding the embodied nature of cognition (Varela et al., 1991) as deeply dependent upon and involving bodily experience, perception, and action have revealed limitations of extant instructional practices in offering full accessibility to learners with disabilities (de Freitas, 2016). An implication of embodied cognition is that accessibility entails building from the ways that learners interact with the world through their bodies (Tancredi et al., 2022). That is, the design of more accessible instructional technological *media* is predicated upon building from learners' existing embodied resources, specifically catering to the sensorimotor *modalities* that enable them to develop new ways of perceiving and acting on the environment (perception–action loops) as the basis for conceptual understanding (Hutto et al., 2015). However, the Learning Sciences have yet to develop robust models of BLV youth's *embodied epistemic practices*, so that the field is currently under-equipped to design pedagogical resources for their STEM teaching–learning interactions. In this co-design study, we are collaborating with BLV youth to explore their embodied epistemic practices, with a research focus on haptic sense-making of complex dynamic phenomena.

3. Methods: Co-Design and Design-Based Research

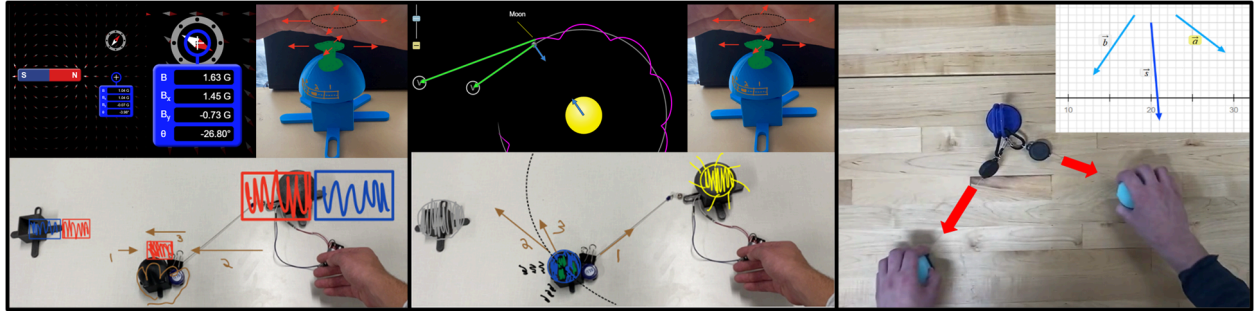
3.1 TeleTangibles Design

TeleTangibles entails iterative rounds of co-design with BLV and sighted participants to develop, explore, and test new haptic technologies pairable with virtual education simulations for accessible middle school STEM learning (Authors) (Figure 1). TeleTangibles are conceptualized as low-cost 3D-printed tangibles with embedded sensors and electronic actuators that can be used as digital twins (Singh et al., 2021) of virtual learning experiences (Figure 2). Current iterations use 2D computer vision to track the movements of tabletop tangibles within a customizable virtual environment¹. Prototyping of the paired virtual-tangible system was built using open-source Paper Playground software, which leverages browser-based scripting, dot-encoded papers, and a web-cam to mediate participant interaction with a tangible to the virtual experience and vice-versa (Fiedler et al., 2024; Ranjan et al., 2025). We designed modular 3D-printed tangible prototype assemblies to enable customization of physical shapes, sizes, and textures and interchangeable internal electronics to customize haptic feedback for pedagogical activity and user preference.

Figure 1

Example TeleTangibles STEM Applications: Magnetism, Orbits, and Vectors

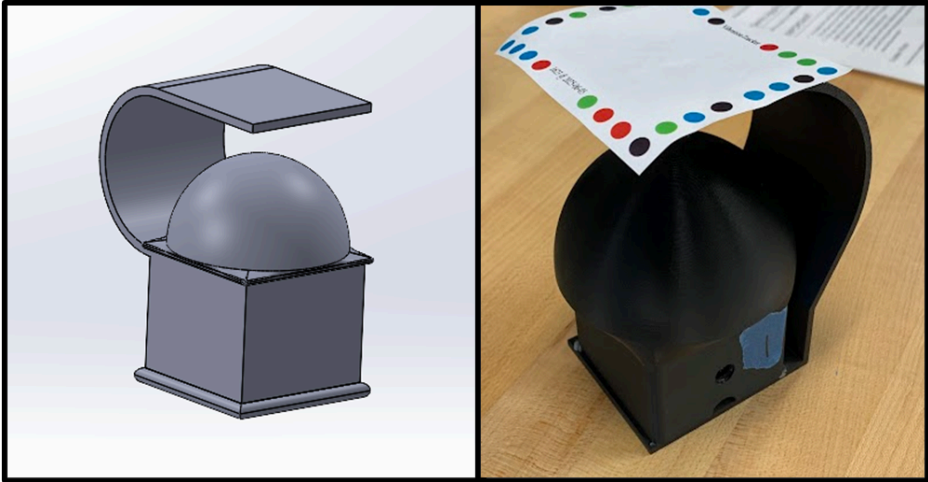
¹ Interaction with the virtual environment is not required to utilize the tangibles: virtual environments created with cause and effect logic can signal actuators in the tangibles that can provide haptic feedback to the user based upon the tangibles position and or motion. This allows for a purely physical experience for the user while still utilizing the electronic/digital based tracking and feedback capabilities of the system. Under development are virtual-to-tangible and remote tangible-to-tangible capacities to enable flexible-modality, multi-locational co-learning.



Note: Tangible interactions illustrating use cases for TeleTangibles tangible digital twins. The graphic on the left depicts utilizing position control paired with skin drag (conveying direction and intensity through movement of a joystick-like element felt under the palm) to represent a magnetic field and its resulting forces. The graphic in the middle depicts utilizing position control with physical tethers, skin drag, and vibrotactile feedback to represent orbital radii, force/velocity vectors, and cosmic events (such as eclipse). The graphic on the right depicts utilizing physical tethers to represent vectors and their summations.

Figure 2

Tangible Modules Used in Demos



Note. These 3d-printed modular sliding tangibles feature a rounded surface to grip, an overhang arm that arches above the hand for computer vision-based tracking of the tangible’s location, and a modular base that can include elements such as a vibration motor.

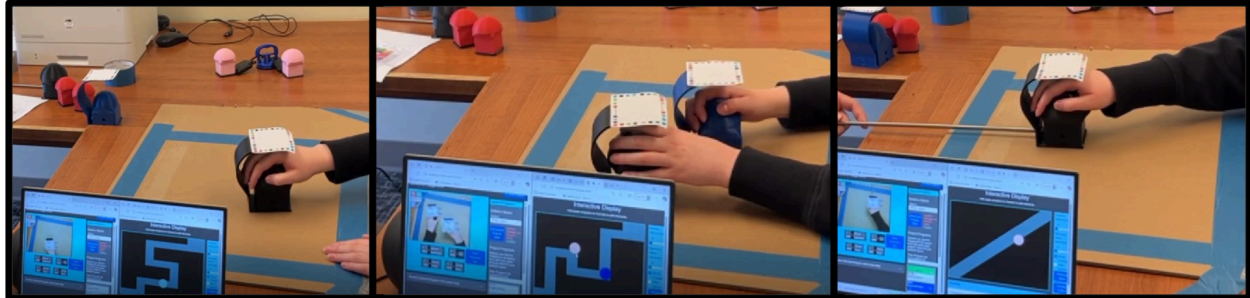
3.2 Data Sources and Analysis

We conducted a user study with 8 youth (ages 16-21, see Appendix I for participant demographics) at a summer program for blind and low vision (BLV) adolescents and young adults. These video-recorded task-based interviews (38-48 mins) included demos of example haptic technologies (Table 1-2, Figures 3-4) and open-ended questions (Appendix II) to invite participants to ideate about features of their ideal math and science learning tools. The function

of prototypes was to give participants access to examples of haptic interaction possibilities that could open up the design space for them.

Figure 3

Photographs of Core Demos



Note. For all three maze tasks, paper attached to the top of the manipulative tool conveys the hand's location within the maze area (delineated by tape). Using computer vision, the hand's location is tracked within a virtual maze and provides auditory (Demo 1A), vibratory (Demo 1B), or audio and vibratory (Demo 1C) feedback about the hand's location. In the cooperative maze, the researcher simulated remote actuation of the tangible by pulling it with a wooden dowel.

Table 1

Descriptions of Core Demo: Maze Navigation

	1A: Single hand maze, audio feedback	1B: Dual hand maze, audio feedback	1C: Dual hand maze	1D: Cooperative maze
Illustration	Figure 3A	Figure 3A	Figure 3B	Figure 3C
Description	They heard one sound when they were off the maze and another when they had returned to the maze.	They experienced continuous vibration unless they exited the maze path.	They used two hands, one with audio and one with vibration feedback.	Researcher uses a stick to move Researcher moves the tangible in y, and participant in x.
Focal experience	kinesthetic exploration with audio feedback	kinesthetic exploration with audio feedback	dual-hand ² explorations with distinct roles	joint manipulation of a shared object
Prospective applications	Exploring spatial representations	Exploring spatial representations	Exploring multiple streams	co-manipulating sensing/

² Prior work has found that blind students more readily leverage the symmetrical nature of their body than sighted learners for exploration, using both hands (Ali Fernandes & Healy, 2013).

			of information	actuating tangibles at a distance Decomposing movement into multiple components (such as x and y in the coordinate plane)
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Note. In all core demos, co-designers navigated a virtual ball down a virtual maze by sliding a handheld manipulable over the desk. These demos were explored by all participants. Participants were also given the chance to feel embossed outlines of the mazes after demo 1.

Figure 4

Photographs of Auxiliary Demos: (A) Anchor and Tethers, (B) Skin Drag Module (right)



Note. In demo 4, the suction cup provides an anchor point for tethers that can be fixed at a set length. For demo 5, some co-designers (depending on time constraints) were shown how the skin drag module would operate by applying skin drag with a soft ended stylus to the top of the hand. At this stage in the project, we envision this could be useful in conveying vectors. This image shows how the skin drag effect would be automated.

Table 2

Description of Auxiliary Demos

Demo	Demo 2: Anchor and tethers	Demo 3: Skin drag
Illustration	Figure 4A	Figure 4B
Description	Co-designers were shown how the tangibles could be anchored to a set point using tethers to a suction cup	Co-designers were shown how the skin drag module would operate by applying skin drag with a soft ended stylus to the

Demo	Demo 2: Anchor and tethers	Demo 3: Skin drag
	anchorpoint.	top of the hand.
Focal experience	Manipulations relative to a set point; experience of directionality	Feedback on direction and magnitude
Prospective applications	Exploring spatial relations, as in geometry	Experiencing dynamic variation, as with a magnetic field

Note. These demos were explored by only 2 participants who moved more quickly through the core demos.

Using a grounded theory approach (Muller, 2014), we analyze data from first-round co-design interviews with BLV youth towards the following research question: *How do BLV youth experience and imagine spatial exploration through haptic interactions?*

4. Preliminary Results

At this early stage of our analysis, several themes have emerged from youth’s reflections (to be updated with the full analysis). We present data from Participants 1(17M, low vision) 2, (16F, blind since birth), and 5 (18F, blind since age 2).

Distinguishing Cognitive Affordances of Spatial Interactions

Learners’ reflections on the affordances of different haptics media highlighted different forms of spatial perception. Taking the case of P5, she found mobile tangibles with vibration feedback prospectively useful for conceptualizing phenomena involving *dynamics* (“how things move”) and *transformations* (“being able to feel the change.”) P5 further explained her experience of *combining* haptic sensations: after experiencing Demo 3 (skin drag), she expressed its usefulness when used in tandem with the moving tangibles for understanding *relationships*, for example to clarify the concept of molecular attraction from her chemistry studies (“what slides past each other,” “what’s not attracted to each other”), and she distinguished haptic affordances for gleaning local versus global features of phenomena (cf. Banik, 2006), for example touching an embossed outline of a maze productively discloses the holistic form of the activity arena (“get[ting] the general shape”). P2 proposed differentiating *topographic* and *dynamic* information as distinct auditory feedback to indicate different areas or “rooms” in a map-based game.

P5 explained to us a particular cognitive affordance of spatially instantiating STEM phenomena that she experiences as critical for her sense-making, namely that spatiality facilitates her coordinating among information encoded in different semiotic registers (Duval, 2017). She noted that when performing calculations in algebra/precalculus at school, she did not have a sense of “what that would look like on a real graph,” even when using an audio graphing calculator—t “wasn’t as easy to remember.” In contrast, she noted, with the tangibles she “could have done a calculation [and] generated something I could feel,” highlighting the important cognitive utility of being able to *reference prior ideas*. Here, the spatial property of educational artifacts affords not only space-dependent sensory modalities (e.g., vibro-tactile) but also *coordinating information encoded in symbolic expressions across different semiotic registers*.

Sensory Experience and Immersion

Participants' comments revealed criteria impacting their real and imagined experiences of immersion. P2 highlighted the need for multisensory feedback to create immersive experiences. She commented,

I feel like visually impaired people would have a hard time feeling like they are actually in the [virtual] world. And so I think if there were items that they could touch, smell, manipulate, whatever, then that would make them feel a little bit more immersed.

She proposed that even for a tactile or haptic interaction, hearing is paramount:

When you're blind, your ears / hearing is your most powerful sense. I think you kind of get a sense of where you are, yes, from what you touch, but also what you hear.

She broke down auditory phenomenology into *location* (in front or behind the body), *echo*, and *volume*. She then highlighted *touch*, proposing the use of tracked 3d-printed objects that could be made “rubbery, mushy, or slimy,” and *olfaction*, with a “scent blower.” Another factor impacting immersion was goodness of fit with sensory preferences: P1 spoke about his reliance on “muscle–mind connection,” favoring haptic over auditory input: “My brain recognizes the sense and the feeling more.” P5 appreciated the minimal audio in our experiment, because she “like[s] not having too much sound,” which can be “overwhelming,” suggesting designers should consider typical spectra of sensory regulation (Dunn, 2007).

P5's comments highlighted the *egocentric experience* of immersion. She described a virtual chemistry simulation her peers had experienced visually of different kinds of molecules interacting. Imagining accessing the simulation haptically, she said

I would know where I'm going, and then I could kinda play around with [the molecules] and see how they interact with each other. And that way I could learn how they would work in reality.

In her imagined experience, P5's sense of the interactions of the molecules is anchored to her own egocentric movement trajectory: “I would know where I'm going,” and to interactivity: “I could kinda play around.” In contrast to verbal language, the haptic exploration seemed to better afford P5 an egocentric experience of immersion.

Co-Presence and Sharing Agency

Finally, an experiential dimension of haptic spatial exploration discussed by the youth as relevant to conceptual learning was *co-presence* and *negotiating shared agency*. P2 proposed adding a headset voice-chat feature to activities when conducted remotely to better share experiences. P5 noted that during tangible co-manipulation in Demo 1D, she experienced a “tension” from feeling the other player's actions on the object as a resistance to her own actions: “I kind of liked that tension,” because that way one can “know the other person is there, especially if we weren't in the same room.” Participants noted mixed experiences of agency. Reflecting on co-manipulating a tangible, P5 noted, “I could feel where we were going,” a statement connoting a phenomenology of joint action as simultaneously passive (she is feeling the movement) and active (we were going), suggesting an experience of *shared agency* (Loehr, 2022). P1 recognized an extraneously moving tangible as an alterity: he likened the experience of a skin-drag joystick moving on his palm as “like when a doctor has a stethoscope and they, like, move it around.” Being prodded by an information-bearing material utensil that we are not co-manipulating may tacitly instantiate a co-present agentive other. The dynamics of moving objects—their *latency*, *spontaneity*, and *immaleability*—evoked co-agency as a salient dimension of experience.

6. Discussion, Conclusion, and Significance

BLV youths' explorations, reflections, and imaginings reveal cognitive affordances of spatial interactions for conceptualizing dynamics, transformations, relationships, and topographies. Their imaginings of immersion reify the role of multisensory experience and probe the prospective role of body-centered, egocentric perspectives in enactive imaginings (Pouw et al., 2017). Prior work has found that BLV youth effectively use their bodies as a point of reference in exploring object shapes and dimensions (Klingenberg, 2012), and some express a preference for body-centered (egocentric) perspectives compared to allocentric, 3rd-person perspectives (Pasqualotto et al., 2013). Considering that fluently coordinating egocentric and allocentric perspectives is both indicative and facilitatory of sighted learners' STEM expertise (Abrahamson & Gerofsky, 2024; Gerofsky, 2011), cultivating egocentric experiences of STEM concepts for BLV learners warrants further attention.

Participants' reflections on co-presence highlight the implicit nonvisual ways that the presence and contributions of others are and can be perceived. Experiences of co-presence predict satisfaction in virtual environments (Bulu, 2012). Our preliminary findings suggest that cues such as the "tension" or slight resistance of objects to our touch offer a means to convey the agency of another person haptically, even at a distance, giving rise to an unexplored class of collaborative and remote learning artifacts to facilitate nonvisual copresence and shared agency, which likely would require novel forms of co-operative action (Goodwin, 2018).

Next steps in this work includes further rounds of co-design work with both blind and sighted youth, as well as teachers of the visually impaired and general education teachers, towards developing reconfigurable haptic-digital tools usable in classrooms. Ultimately, we anticipate that through successive iterations, codesign of TeleTangibles can interrogate core Learning Sciences' constructs within nonvisual experience, towards ontological innovations (DiSessa & Cobb, 2004). In particular, as we explore the shift from haptic perception of spatial entities to specific science and math concepts, such as vectors and magnetic fields, we anticipate the emergence of nonvisual gestalt perceptual structures that organize and facilitate action: *attentional anchors* (Hutto et al., 2015), heretofore primarily documented primarily within visual perception in embodied learning settings. Centering BLV learners' embodiment surfaces epistemological pluralism (Turkle & Papert, 1992) in constructing notions of spatial concepts that may lead to meaningful restructurations (Wilensky & Paper, 2010) of math and science domains.

Haptic learning experiences have been found to deepen STEM learning. This study explores haptic experiences that can broaden the range and applications of haptics for BLV students' learning, both as individuals and in collaboration with peers and mentors. This ongoing work can provide a deeper understanding of the phenomenological experiences of BLV youth's interactions with and through haptic and multimodal technologies. Ultimately, learnings from this work can inform more effective and equitable instruction of spatial concepts for BLV as well as sighted learners.

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Appendix I: Participant Demographics

#	Age (Years)	Gender	Grade Level	Primary Diagnosis
1	17	M	Senior	Optic Nerve Hypoplasia
2	16	F	Senior	Optic Nerve Hypoplasia
3	17	F	Junior	High Myopia
4	21	M	College	Bilateral Retinoblastoma
5	18	F	College	Leber Congenital Amaurosis
6	17	M	Senior	Congenital Chorioretinal Dysplasia Syndrome
7	16	F	Junior	Glaucoma
8	18	M	Freshman	Optic Nerve Hypoplasia

Appendix II: Demo-Related Protocol Questions

What about each feedback (the sounds and the vibrations) did you like and not like? What helped you stay on the path? Can you think of other ways the tangibles could have let you know whether you were on the path or not?

Can you share any initial thoughts on how the tangibles feel? Is there anything you can think of that you want to do with them or wish you could do with them?

Do the tangibles or balls remind you of any tangibles or learning tools you have used before? What were those tools? How are they similar and different from what you just used?

Does this maze activity or tracking of a path remind you of any topics you learned in math and science? Can you think of any topics where tangibles like this might be useful?

How did you use each hand? What was that interaction like for you? What made it easier or harder with two hands?

Can you imagine learning scenarios where this kind of interaction with two hand movement and exploration would be useful?

Can you imagine any contexts where having someone else be able to control the thing you are moving in an activity like this could be useful or interesting?

How did it feel to move the ball down the path together? Did you feel like you could tell or anticipate what I was doing? Did that change over the course of the path? Did it feel like at certain points you were leading or following? How could you tell which one?

Can you imagine any contexts where this kind of shared action could be useful or interesting in learning?

Can you think of any math and science topics you struggled with and how these tools could have been helpful to learn with and how?

Acknowledgements

Data analysis for this paper was conducted by Sofia Tancredi, with input from Dor Abrahamson. The data discussed in this paper were collected by Colton Doherty, using a protocol developed collaboratively by the project team. The demo interactions were designed by Colton Doherty and Sofia Tancredi with input from the full team and Jenna Gorlewicz, and built by Matthew Murawski, Kody Cool, Nomin Erdenebileg, and Colton Doherty. Custom paper playgrounds environments/projects were completed by Matthew Murawski and Kody Cool with support from Colton Doherty and Jenna Gorlewicz. Paper Playgrounds was designed by Brett Fiedler together with the PhET Interactive Simulations team. We thank our codesigners for their insightful reflections and ideas and our partners at the summer camp.