TASC: Combining Virtual Reality with Tangible and Embodied Interactions to Support Spatial Cognition

Jack Shen-Kuen Chang[1,2], Georgina Yeboah[1], Alison Doucette[1], Paul Clifton[1,4]
Michael Nitsche[4], Timothy Welsh[3], Ali Mazalek[1]
Synaesthetic Media Lab, Ryerson University, Toronto, ON, Canada[1]
Polytechnic Institute, Purdue University, West Lafayette, IN, USA[2]
Faculty of Kinesiology & Physical Education, University of Toronto, Toronto, ON, Canada[3]
Digital Media, Georgia Institute of Technology, Atlanta, GA, USA[4]
JackSKChang@gmail.com, gyeboah@ryerson.ca, alison.doucette@ryerson.ca, paulgclifton@gmail.com,
michael.nitsche@gatech.edu, t.welsh@utoronto.ca, mazalek@ryerson.ca

ABSTRACT

A growing body of empirical evidence from the cognitive sciences shows that physical experience can enhance cognition in areas that involve spatial thinking. At the same time, virtual environments provide opportunities to engage learners with novel spatial tasks that cannot be achieved in the real world. Yet combining virtual worlds with tangible interfaces to engage spatial cognition is still not a well-explored area. This paper describes the TASC (Tangibles for Augmenting Spatial Cognition) system, which combines movement tracking and tangible objects in order to create a strong sense of embodiment in a virtual environment for spatial puzzle solving, designed to engage perspective taking ability. We describe the motivation, design process, and development of TASC. We also report the results from our user study, showing the participants' positive experiences, linking to future research opportunities.

Author Keywords

Tangible interaction; embodied cognition; virtual reality; virtual environments; spatial cognition; games.

ACM Classification Keywords

H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems--*Artificial, augmented, and virtual realities*; H.5.2 [Information Interfaces and Presentation]: User Interfaces--*Input devices and strategies, interaction styles*; J.4 [Computer Applications]: Social and Behavioral Sciences--*Psychology*; K.8.0. [Personal Computing]: *Games*.

INTRODUCTION

Success in STEM (science, technology, engineering and mathematics) learning has been shown to be highly correlated to spatial ability. Over the last several decades, research efforts have continued to offer evidence or observations of such a link. After World War II, the United States recognized the need for growing the number of scientists and engineers in the workforce and commissioned a research study to understand how to improve spatial ability [36]. One result of the review, reported by Super and Bachrach in 1957, showed that successful engineers tended to share the characteristic of highly developed spatial ability. Several longitudinal studies launched since then, such as the Study of Mathematically Precocious Youth (SMPY), have aimed to further investigate this link between spatial ability and academic and career performance [22,35]. In 2009, Wai et al. examined these 50 years of research, with samples extracted from 400,000 participants tracked for at least 11 years [40]. Wai's study results aligned with those in the SMPY [22,35], and indicated that spatial ability can be a strong predictor of STEM performance.

Those studies have been broadly interpreted as a recommendation that the education system should support and improve spatial ability. However, even though the connection is widely accepted, in practice, this need remains pressing today. The 2012 Report to the U.S. President still asks for one million additional graduates in STEM degrees [27]. To support this growth, the recommendation of increased spatial ability has been taken up by researchers from many disciplines over the last several decades, and among other things, has led to the formation of the *Spatial Intelligence and Learning Center* (SILC), a U.S. National Science Foundation (NSF) *Science of Learning Center (SLC)*.

Particularly relevant for this work are theories in embodied cognition and common coding that are based on the notion that there is a tight relationship and activation between perception, cognition, and action codes. Based on these theories and the evidence that performing spatial tasks involves the motor system, recent research in the field of TEI (Tangible and Embodied Interaction) has shown a link between embodiment and spatial cognition using interactive systems [24,25]. Motivated by those projects and the clear

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need for more spatial cognition support in education, we aim to leverage tangible and embodied interaction design to engage and support spatial skills.

In this paper, we describe TASC, a system that creates a strong sense of embodiment in virtual reality (VR) with movement tracking (head and hands) and tangible object manipulation. The system engages the spatial skill of perspective taking by requiring a user to work from multiple points of view to solve a series of virtual puzzles. Our research makes contributions to three main areas: 1) We provide an overview of the project's related literature, which motivated and guided our work; 2) We share the participatory and iterative design process, which includes design goals and lessons learned. They together led to a final implemented system, which included technologies used to establish/support embodiment, and spatial design features that engage perspective taking ability with increasing difficulty; 3) We conducted a formal user study for the final system. We present the results, followed by discussion and future work.

BACKGROUND

Our research and the design of the TASC system draws from three related areas of cognitive science: embodied cognition, common coding, and spatial cognition. Insights from and the connection between these areas led us to the hypothesis that engaging the motor system during interactions in the virtual world can help to create a strong sense of embodiment in a virtual environment. This embodiment, combined with the immersive nature of virtual environments, can be leveraged to support spatial skills through the common coding link between perception and action. To make this point clear, we outline research in each area and then draw connections between them.

Embodied Cognition

While this topic is formulated and studied in different fields (philosophy, phenomenology, social interaction, etc.), this paper focuses on the cognitive science aspect of how systems engage the body and motor actions. Theories of embodied cognition are based on the notion that cognitive processes, such as perception, reasoning, and language, are situated in and shaped by our bodies and the active way we interact within the world. In other words, motor systems are not output structures that passively receive the results of cognitive processes, but motor and cognitive systems are intricately related to one another. Hence, the motor system is actively involved in cognitive processing. In this way, cognitive processes can affect bodily states and actions, and bodily states and actions in the environment shape our thinking. This tenet is supported by numerous studies that demonstrated for example the activation of the motor system and biasing of action during speech perception [19], the benefits of simultaneous action on mental rotation [44], and the biasing of perception by the action state of the system [4].

Common Coding Theory

Common coding or ideomotor approaches to perception-action coupling provide one useful framework and set of mechanisms through which perception, cognition, and action systems are linked and shape one another [14,15,29,30]. The core notion of ideomotor theory is that, through the repeated execution of action, the knowledge (or its neural representations) of the perceived effects that those actions have on the environment become tightly linked or bound to the neural codes that lead to the action itself. The implication of this tight coupling is that activation of one code leads to the activation of the associated codes: the perception or imagination of motion or action leads to the activation of the motor system, and selection of motor plans can lead to the activation of associated perceptual and cognitive codes. Thus, active exploration of objects and the environment develops associations between representations within perception and action systems, and these associations can subsequently be leveraged to enhance other cognitive processes such as language and memory.

Of critical relevance for our approach, Kontra et al. found that people who actively interacted with physical systems during the learning of content related to the physical effect of angular momentum demonstrated a greater understanding of those physical principles than people who simply observed the interactions [18]. The degree of sensory and motor system activation in the brain correlated with test performance. This research indicates that interaction and sensorimotor system engagement enhanced the learning and recall of content.

Spatial Ability

Spatial ability is defined as the ability to process and act on spatial information from the environment. Spatial information can include the geometry of an object, relationships like distance between two or more objects, or routes and landmarks as experienced during navigation [6] among other options. Cognitive science has shown that people's perceptions of spatial features of the environment are influenced by the state of the body. For example, people wearing heavy backpacks report that hills look steeper [31]. Other studies have shown that people incorporate tools into their body schema and report that objects appear closer and more reachable after they have used a tool such as a rake [43].

Existing spatial ability evaluations used in cognitive science and psychology studies provide insight into specific ways that a spatial skill may be linked to the body. These evaluations are derived from an operational definition of the skill: a description of how that skill is enacted and how it is quantified. The tasks used in these evaluations often involve imagining movement, either of the body or of the objects in an image, and selecting a representation of the result of those movements or making some inference about the final state of the objects. The tasks described in the spatial ability evaluations provide a basis for the design of applications and interventions that engage that spatial skill [3].

RELATED WORK

Our work builds on previous research on the design of tangible and embodied interfaces that support STEM learning and research. Because our research includes the design of games to further engage cognitive skills, we also look at the context of Serious Games research. To motivate participants, the TASC system uses a puzzle-like design, which is an approach that has been used in Serious Games for STEM education in other areas as well. However, TASC focuses on building broad cognitive foundations for future research in STEM through an emphasis on spatial cognition rather than on individual problem-solving.

TEIs for STEM and Problem Solving

There are numerous examples for TEIs supporting education in STEM fields. Many of these provide embodied tools intended to support STEM learning and problem solving through novel interfaces. For example, Raffle et al.'s Topobo is a construction kit with kinetic memory that helps to introduce basic physics concepts such as center of mass, balance and gravity to young children through hands-on interaction [32]. The work of Price et al. demonstrates how both the manipulation of tangible objects as well as bodily movement in space can support learning of physics concepts, such as the physics of light, as well as concepts of motion and acceleration [28]. More recently, Okerlund et. al.'s SynFlo uses a tangible tool consisting of active tokens and an interactive tabletop to introduce groups of users to biological engineering through a bio-design activity [34]. These examples all share an approach that leverages tangible and embodied interaction design to make abstract scientific concepts and systems more accessible to users. However, none of these projects specifically aims to support and augment spatial abilities.

Other researchers have investigated how tangible interfaces compare with graphical interfaces in supporting design and problem solving tasks. For example, Kim and Maher [17] studied tangible vs. graphical interfaces in design scenarios and found that the designers using the tangible interface tended to communicate their ideas by moving objects physically, while those using the graphical interface relied on verbal communication. They found that tangible physical actions allowed the designers to better leverage their spatial and kinesthetic senses to aid cognition. Antle and Wang compared the motor-cognitive strategies used for solving puzzles with touch vs. tangible interfaces [1]. Their work investigated the number of epistemic and pragmatic actions used to put together a jigsaw puzzle using either physical pieces or virtual pieces on a touch interface. The results showed that people use different strategies for solving problems depending on the affordances of the interface.

More directly related to our own work, the emBodied Digital Creativity (BDC) project showed that a physical puppet interface that maps body movement on to virtual characters could be used to augment spatial cognition and creativity. Specifically, the results showed that mapping a user's body movement onto a virtual character increases identification and that this identification can be leveraged, through game design, to improve mental rotation ability [24].

VR and Serious Games

Technological progress and commercial marketing has turned VR into a consumer media with new opportunities for immersion and targeted impact. Serious Games applications have been suggested and discussed, for example in healthcare [23], even before the release of commercial systems such as the Oculus Rift, the Samsung Gear VR, or the HTC Vive. Not surprisingly, they have also been applied to recent Serious Games work. For example, Serious Games continue to adapt them for virtual laboratories [21], education [39], professional training [42], and healthcare [20]. The resulting approaches have led to a mixed reality design that supports a form of "kinesthetic interaction" that includes bodily interactions more holistically [8].

Designing Tangibles for VR

Eminent scholars envisioned how digital content and interactions can enrich human activities in the physical spaces. For example, Ishii and Ullmer's idea of "Tangible Bits" outlined how graspable objects and ambient media can better support attention and awareness [16]. Mark Weiser and John Seely Brown delineated "Calm Technology" for ubiquitous computing, noting that certain physical technologies should "inform but [not] demand our focus or attention" [33,41]. More recent studies have shown how tangibles can be added to support VR content to provide more modalities of sensory experience. For example, Snake Charmer's robotic arm feeds an object of corresponding shape, texture, and temperature per the user's virtual interaction [2]; Annexing Reality finds the best-available physical object to provide a better haptic sensation for virtual objects [13].

Yet, the process of designing tangibles for virtual content (or the other way around) is still not well-documented, let alone such design for supporting spatial cognition. Motivated by embodied cognition, common coding theory, and their correlations with spatial cognition and physical manipulations, the TASC project set out to design, develop and evaluate a tangible-virtual integrated system for supporting spatial ability.

DESIGN PROCESS

Choosing the Spatial Ability: Perspective Taking

Our work on TASC began with the goal of developing interfaces that support spatial cognition. Among the various spatial abilities we surveyed, we eventually chose perspective taking, which is defined as "the ability to mentally represent a viewpoint different from one's own" [9] . We selected this spatial ability for several reasons: 1)

There are not many, if any, interactive VR-TEI projects designed to engage this ability; 2) Perspective taking ability has been shown to be linked to bodily movement [12,37], making it a good fit; 3) Perspective taking is independent from other spatial abilities, such as mental rotation [12]; 4) Many tests are available to evaluate perspective taking ability, such as Hegarty's PTSOT (Perspective Taking/Spatial Orientation Test) [11], Frick et al.'s Perspective Taking Task [9], a perspective taking performance test designed for kindergarteners, and the Purdue Spatial Visualization Tests: Visualization of Views (PSVT:V) [10]. These tests can be used to inform the design, or be used as future assessment tools; 5) It is a spatial ability that can change and develop beyond a certain age instead of remaining fixed after childhood [5,26,38], i.e., it is malleable. Together, these reasons indicated that there is value in building a new VR-TEI system designed around perspective taking, and that such a system could potentially be evaluated using existing tests in order to understand its effects on users' perspective taking ability, especially for adults (e.g., undergraduate students).

Ideation with Participatory Design

After deciding on the target spatial ability, we went through brainstorming sessions in several formats and stages. Although we kept in mind that the main goals were to engage perspective taking spatial ability and to establish embodiment, the research team employed "blue sky thinking" ideation methods (not using the goal as much as a constraint) to generate novel and exploratory system design ideas with sketching, wire-framing, and quick prototyping.

During these stages, we also brought the project to a student group in an embodied/tangible media design and research course taught by the team's supervising professor. The student group (a mixture of 5 undergraduate and graduate students who were in STEM or design related majors) provided additional design input while gaining research-oriented design experiences.

Additionally, we held a one-day workshop with 9 teachers: 8 of them are K-12 teachers (ranging from teaching kindergartens to high schools), 1 of them was an early-childhood education professor who taught at a university, and often trained K-12 teachers. These 9 workshop attendees taught subjects in STEM or art/design (e.g. sculpture, 3D modeling) subjects. In the workshop, we provided seminars on theories and technologies about multi-modal, embodied, and tangible interactions. We also showcased some of the project's tentative sketches, schematics, and technical prototypes. In turn, the teachers shared experiences, challenges, and needs about STEM education. They also offered insights and opportunities about introducing virtual reality and tangible/embodied interaction to support spatial ability for STEM learning.

We summarized the following high-level design goals (G1 to G4) from those 3 design activities based on their preliminary lessons learned.

***G1) Perspective Switching*:** To engage perspective taking ability, the system should allow or even require the user to constantly switch perspectives. This resonates with existing paper-based perspective taking tests and training material.

***G2) Appealing Content Design*:** The content of the system should appeal to students, i.e., it is more important to create an enjoyable and engaging experience than attempting to tie the perspective taking ability with a certain subject matter. Introducing game mechanics or pleasant visuals would be promising directions to achieve this goal.

***G3) Establish Embodiment*:** Involving the body does not necessarily mean asking for users' intense, active, or full-body movements like those performed in exer-gaming (a form of video game that is designed for the purposes of fitness or physical therapy). Embodiment can be established and augmented in many ways. The bottom line is that the new design functions beyond just WIMP-based control (windows, icons, menus, and pointers) and surfaced-based displays (which are traditional interfaces, considered as low embodiment). This supported our initial idea of combining virtual and tangible interactions as potential ways to establish embodiment.

***G4) Setup and Generalizability*:** The system can be used in classroom settings. The goal of the research is to develop a system that could ultimately be integrated into STEM learning environments. While surveying and choosing a particular subject matter is out of the scope of the research (because we planned to focus on engaging perspective taking ability), these conditions should be paid attention to: 1) The space the system needs is big enough to facilitate bodily movements, and small enough that it does not require much extra setup. Therefore, designs that involved large displays or even a CAVE system (cave automatic virtual environment) were excluded); 2) To make the design transferrable and generalizable, it is better that the system uses off-the-shelf hardware, and open-source or affordable software.

First Significant Generation

Our design process was participatory and iterative in nature, therefore there were many versions of technical prototypes. Here we describe the first more formulated generation (Gen1). The description is in the form of a scenario walkthrough.

TASC Gen1: SkyBridge includes a linear series of puzzles that involve moving blocks to allow a character to cross a bridge over an infinite chasm. In the real world, the player stands in front of an interactive tabletop with two blocks on it and puts on an Oculus Rift with a Leap Motion controller attached to the front of it. In the virtual world, the player is standing on a floating platform (it is the start of an unsolved puzzle, also the end of the previous solved puzzle). She can look around and see other platforms in the sky and nothing below her. When she holds her hands in front of her, she sees the rendered virtual hands and they move the same way her physical hands move. In front of her is a bridge that is blocked by one of a pair of rectangular walls. Through the wall, off to the player's right, is a tunnel, which the player can see from the platform. There is also a graphical element that the player can touch to switch perspectives.

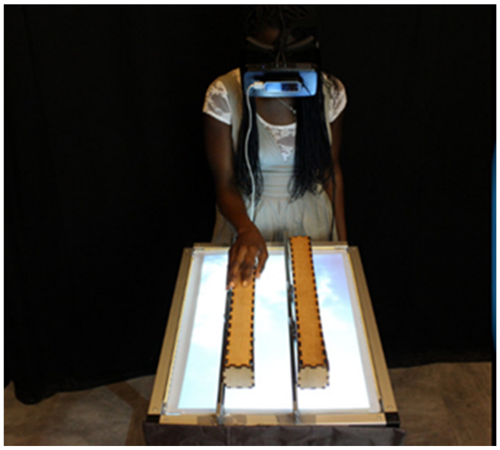

Figure 1. Gen1 user grasps physical block on an interactive tabletop. (Gen 1 used computer vision to track the block positions.)

Placing the virtual hand on the graphical element puts the player in an orthographic, top-down point of view. A bridge is visible that connects two platforms of one puzzle, but it is blocked by the two giant rectangular walls. The tunnel in each wall is not visible from the overhead point of view. In this perspective, the player's hands are large enough to grab and move the walls. When the player reaches out to touch one of the walls, she feels, in the real world, a physical object with the same shape as the walls in the virtual world.

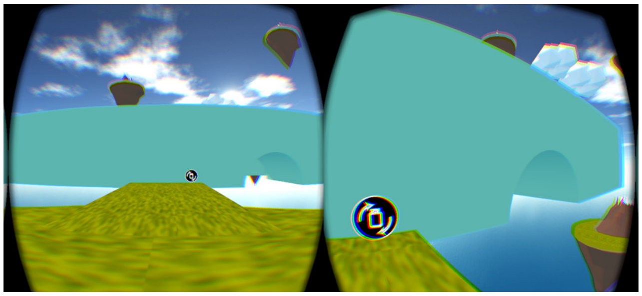

Figure 2. Gen1: Left – starting view showing blocked bridge and tunnel. Right –graphical element for switching perspectives

When she moves the physical object (the wooden block), the virtual wall moves in the same way. The movement of the objects in the real world is constrained by a rail, so she can only slide the walls along a single axis, and not pick them up and remove them from the bridge. Hence, in the ground perspective, she can see where the wall tunnels are but she cannot move the walls; in the overhead view, she can move the walls but cannot see the positions of the wall tunnels. She switches between the two perspectives iteratively to move the two walls (by physically moving the wooden blocks), with the goal of creating a pathway by aligning the tunnels on the two walls together. Once the two tunnels are aligned, the bridge becomes cross-able. She holds the two arms up horizontally as a "move forward" gesture, to navigate herself to the next puzzle. She finishes the game by solving all the puzzles.

In this Gen1, each block was constrained by a rail so the block could be moved linearly. The bottom of each block was tagged with a fiducial marker, tracked by the table's computer vision functionality, made with 2 cameras (each one covered half of the table's surface), the CCV software, and TUIO message passed to the central Unity 3D application. The choice for building the interactive tabletop to track the blocks was based on the consideration that other tangibles might be added later.

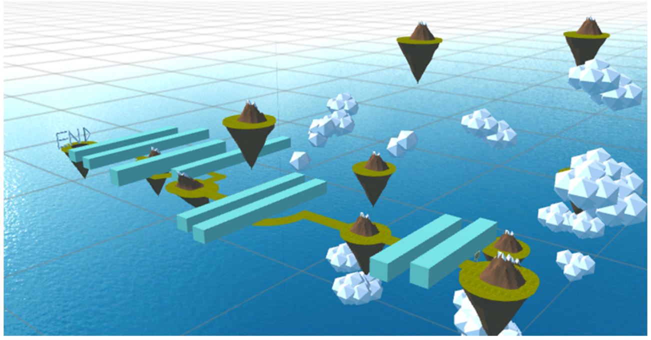

Figure 3. Gen1 "SkyBridge": A series of puzzles on a long bridge

Informal Evaluation for TASC Gen1

We conducted an informal evaluation with 7 lab members who were not involved in the design process. They never tried any of the evolving versions prior to joining the evaluation. The evaluation was informal and part of the iterative design process, i.e., a later participant might experience a minor new feature or technological fix that was added per the evaluation results or suggestions from an earlier participant. But overall, the 7 participants tested with similar derivatives of Gen1. Each of them solved every puzzle in this generation.

In general, they found the experience novel and interesting, given many of them had not interacted with VR content, especially with tangible interaction. They also mentioned using their perspective taking ability a lot to solve the puzzles, which was an indication that this spatial ability was engaged.

However, these problems emerged among many of the informal evaluation's participants: 1) The simple, low-poly art, looked underwhelming and without a theme; 2) It felt somewhat dangerous to have to virtually stand and walk on a long bridge that was suspended in the air; 3) To finish the game, one needed to navigate from one solved puzzle to the next unsolved puzzle by holding her hands up in front of her. Doing so was reported to have cost extra kinesthetic effort and motor coordination. We suspected that one of the causes was the user's physical body remained still (standing in front of the system) while the virtual body was moving forward. This became a bigger issue when certain users reached a winding part of the long bridge; 4) Minor simulator sickness was reported among some of them. We suspected 2) and 3) to be potential causes; 5) Since the block-tracking was made with computer vision in the interactive tabletop, it put more computational demand on the system which led to a less satisfactory rendering performance in the virtual world.

We analyzed the user feedback and developed more sub-versions. Below we present the final design of **TASC (Gen2, "Finding the Horse")**, followed by how certain design choices were made to address the issues we found from the first generation, i.e., how the iterative and formative evaluation drove our design. We then report the protocol and findings from this final design's evaluation.

TASC: FINAL DESIGN AND IMPLEMENTATION

In this section, we illustrate how the second significant generation of TASC was designed and implemented. Some designs and technological features were seen in Gen1. In this section, we provide a formal and complete description about how they were chosen or kept. (From now on when "TASC" is mentioned, it refers to this Gen2 version.)

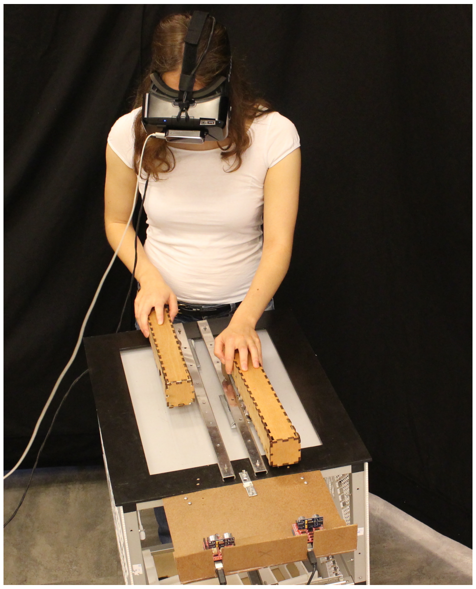

Figure 4. The physical setup of the TASC system

Supporting Embodiment

The TASC system builds on embodied cognition and provides several features that serve to embody the player in the virtual environment (VE). This can be broken down into 3 aspects as shown in Figure 4. First, the user wears an Oculus Rift head mounted display (HMD), which tracks her head movements and provides a 3D immersive view of the VE. The TASC system updates the in-game viewport in real-time to follow the user's head movement, reinforcing the sense that the user is inside the game world. Second, a Leap Motion controller is attached to the front of the HMD so that the user's hand (and finger) movements can be captured and rendered accordingly as virtual hands in the VE. The head and hand tracking both serve to enhance embodiment by reinforcing the sense that the virtual body is the user's own real body. Third, a table with two long tangible blocks is placed in front of the user. Each block can only be moved along the same axis as its movements are constrained by a rail. A block's movement is captured with a corresponding ultrasonic distance sensor. The blocks, designed and made of wood, add sensory coherence to the virtual fences, which are textured as wooden slabs in the VE. The design aims to make touching and moving the physical blocks a tangible experience that is directly transferrable to the VE: one moves the blocks to move a pair of virtual fences in the game world. The role of the fences in the VE is described in the following subsection.

The VE is a game that asks the user to solve a series of puzzles by making use of their perspective taking ability. The game is made in Unity 5.3 (programmed with C#). To track the user's head and hand movements, Oculus Rift and Leap Motion SDKs were integrated in Unity. Arduino and COM port connections were also added in Unity to detect the blocks' linear travels by taking signals from the ultrasonic sensors. Free 3D models were downloaded from the Unity Asset Store and modified to construct some of the VE.

Core Gameplay

The VE consists of a farm with structures such as a cabin, windmills, bushes, and a stack of logs. It includes a horse whose initial position is always separated from the user's ground character position by two long fences. Somewhere within each fence is a wider opening. In each level, the goal is to move the physical blocks to align the virtual fences' openings, revealing a pathway for the horse to run toward the user's ground position in the farm. The user has two main perspectives to solve these puzzles. (Note: Unless otherwise specified with "physical", "real-world", etc., descriptions about what a user can see all indicate what she sees in the VE since she wears a VR HMD.)

The Ground View (GV) (Figure 5): This is a first-person view in which the user's virtual character is situated on the ground. In this view, the user can only look around, and cannot move around in the virtual space. With this view in the VE, she can see the opening of the near fence by looking around, as well as the approximate position of the opening of the far fence (the fence closer to the horse). She can also look around to see the surrounding objects, e.g., her spatial relationship to the cabin, or the windmill. However, the user cannot move the fences in this view. For this, the user has to switch to the Aerial View. (In GV, the user can surely move the physical blocks if she wants to. But in GV, the physical blocks' position changes will not

**Figure 5. Ground View (GV)
(Top: before the puzzle is solved;
Bottom: the puzzle is solved, the horse runs toward the user.)**

**Figure 6. Aerial Views (AVs)
(Top: normal, 0º view; Lower left: 180º, the mirroring view; Lower right: 90º view)**

be applied to the fences.) Hence, GV is the "solution progress view", and actions (of moving the blocks) are effectless.

The Aerial View (AV) (Figure 6): In this view, the user looks down onto the farm from a bird's eye view. This is also a first-person view, and also a view within which the user can only look around and cannot move around in the virtual space. In this view, the user receives an overview or outlook of the spatial relationship of the farm's objects: the farm's structures, the horse, the fences, and the ground character's position (where GV is located), which is a short orange cylinder with text label "You" (hence, the "you-icon"). However, the positions of the fences' openings are hidden in this view. Seen from above, each fence appears to be a long continuous structure with its opening hidden from the user. This is achieved by dynamically generating a piece of wooden slab to fill each fence's opening every time this AV is entered. Although fence openings are hidden in AV, this view is the "action view". Only in this view the user can change the positions of the fences by moving the physical blocks along their rails. Each block controls a corresponding fence.

In either GV or AV, there is a UI icon. The user can look at it for 0.5 seconds to switch to the other view. Switching between views is important in the game because in GV, the user can see where the fences' openings are but cannot move the fences, while in AV, the user gets to move the fences, but does not see the current positions of the openings. Therefore, the game challenges the user to keep switching perspectives (GV: "solution progress view"; AV: "action view") so she can carry the spatial information acquired in one view to the other in an iterative manner, which eventually leads to solving the spatial puzzle by aligning the fence openings to form an open path between the horse and the user's ground position. Only then can the horse run through the opening and towards the user character, marking the solution of the spatial puzzle.

Increasing Difficulty

The puzzles in the TASC system are designed to increase in difficulty as the levels progress in order to provide new challenges and track the user's performance over time. This is aimed to continuously engage the user to keep applying her perspective ability while gathering spatial information and constructing strategies to solve the problems.

The variation of difficulties is based on a mix-and-match method of certain spatial features. There are overall 9 levels (9 puzzles). In the first level, the horse is located directly across from the user's GV position, simplifying alignment of the fences. In subsequent levels, the horse is diagonal relative to the user's GV position (the you-icon position seen in AV), forcing them to align the fences based on that angled axis.

Levels 3 and 4 change the viewport angle in the AV – Level 3 rotates the scene 180º, while Level 4 shows the scene from a sideways (90º angle). Starting from level 7, the AV will select randomly from these two angles and the original angle (totaling three possible AVs). Note that across different AVs (the views in which a user can move the fences), the block-fence mapping is the same. As a result, a mirroring effect is at work between fence movements seen in original AV and the 180º AV, which is one of the difficulty features. This design is inspired by perspective taking ability's egocentric and allocentric categorization, as well as Ehrsson's virtual illusion study out-of-body experience (seeing one's own body from outside the normal perspective) [7]. Note: This multiple-AV design may be questioned for its possible "disembodying" effect. But from the result in our iterative design process, Gen2's pilot study and formal study, we believe the embodiment that is established before and during these multiple-AV levels was not impacted. Hence, this design is more about providing spatial challenges than being disembodying. (Literature does mention certain disembodying setups can actually enhance embodiment, but such discussion is beyond the scope of this paper.)

From Level 7 onward, the user's GV position is hidden in the AV, resulting in the disappearance of the you-icon. This eliminates their immediate knowledge of where their character was positioned in the game world. The user can compensate for this loss of spatial information by checking her proximity to the stationary landmarks in GV, and then finding those same landmarks in the AV. The availability of this strategy (of using surrounding landmarks as reference points) is provided via an in-game hint to the player after 7 seconds have passed (a duration chosen based on the results from pilot studies).

Design Choices

Since we have described the final design of the TASC system, here we explain how certain design choices were made from our iterative design process.

The most important change we made between Gen1 and Gen2 was that we excluded the need for navigation (moving from a solved puzzle to the next unsolved puzzle). Navigation might be a cause of simulator sickness in Gen1. Also, navigation (even in virtual environments) involves many spatial abilities such as mental rotation and distance estimation [45]. Therefore, including navigation meant that we could not be sure that perspective taking would be the primary spatial ability engaged by the user. In the final design, whenever a user solves a puzzle (in a level), it is the horse who runs to the user rather than the user who walks through the tunnels, and the game thus advances to the next puzzle without requiring the user to move forward – the game just generates the next puzzle without asking the user to move virtually or physically. That is also why a level's GV and AV are in fixed positions (the user can only look around but cannot move around in those views.)

Since navigation was not included anymore, we could concentrate on continually engaging the user's perspective taking ability in changing ways. For that reason we have 9 puzzles, and the puzzles become more difficult. If we had fewer puzzles, or the puzzles applied perspective changes in the same way repeatedly and with the same difficulty level, the user might finish the game simply from interface or game familiarity.

From Gen1 to Gen2, we kept the design of using only 2 physical wooden blocks because we did not want to complicate or distract the user with too much tangible manipulation that was not central the perspective changes while interacting with the virtual content. Reducing unnecessary interactions was also why in Gen2, the user could just "gaze" at a UI icon to switch perspectives. (In Gen1, the user needs to lift a hand up from the block in order to move the virtual hand to touch the virtual perspective-switching icon. This might cost a user extra spatial adjustment when placing the hand back on the block. This consideration was also why we did not pursue the idea of using another physical input, like a keyboard or a wearable device, for the user to conduct perspective switching.)

Since the tangible manipulation was aimed to be simple, we eventually used only ultrasonic sensors for the blocks, and discarded the use of the computer vision based tracking software and hardware. This also improved the rendering performance in the VE.

Finally, we chose a farm because it provided an overarching aesthetic and topical theme in which we could naturally add objects like windmill, cabin, fences, etc. The farm also feels like a safe and soothing environment for most people. Most importantly, since the user does not need walk through the aligned openings (like in Gen1), having something coming to the user becomes a good and even rewarding visual cue for solution completion – what symbolizes running in a farm better than a joyfully galloping horse?

EVALUATION

We conducted a user study to understand how people would interact with the TASC system. The pilot study participants' responses and feedback helped the stabilization of the system and the finalization of the evaluation protocol, which is described below.

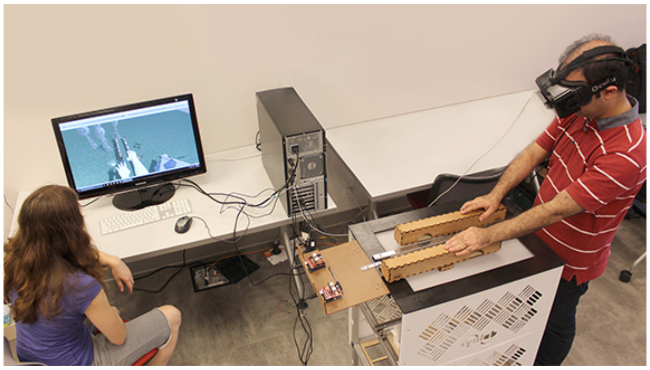

Figure 7. Evaluation setup (mirrored view in a later level)

A participant, after being greeted and briefed about the study, gave consent by signing the consent form, which he had read prior to arriving the lab.

The participant was taken to the front of the TASC table with the blocks on the table. The researchers helped the participant put on the "HMD bundle" (Oculus Rift and Leap Motion), made sure it was stable and comfortable, and gave the participant a short tutorial. This tutorial aimed to establish proficiency with the novel interaction provided. The tutorial assured that each participant was familiar enough to use and control TASC's tangible and virtual components so their performance or interaction differences will not be a result of unfamiliarity with the system itself.

Having passed the tutorial, he entered the main interaction session consisting of the 9 levels of the horse finding game. There was no time limit for any single level but whenever a puzzle was solved by the participant a researcher gave a verbal prompt ("Now I am going to advance you to the next level.") and pressed a keyboard shortcut of the system's computer to advance him to the next puzzle. Participants did not need to handle the level-advancing because we wanted to focus on the main interaction methods and avoid unnecessary and possibly distracting components in the system that were not related to embodiment or spatial ability. Also, when giving a verbal prompt, the researcher could also ask him if he needed to take a break in case he was experiencing slight simulator sickness. Figure 7 demonstrates a researcher (left) monitoring the participant's interaction with the TASC system.

After playing through 9 levels, the participant was provided with a 3-minute break. Then, he was asked to complete a questionnaire survey about his background and demographics information (age, gender, expertise, major in school, prior VR experience, etc.). His participation was concluded with a semi-structured interview with questions designed to understand his experience.

RESULTS

In total, the pilot study involved 6 participants (3M/3F), the main study consisted of 10 participants (5M/5F). The participants' ages ranged from 18 to 26, and were undergraduate students or recent college graduates whose majors were STEM or design related. Below we summarize our results only from the main study's 10 participants.

The amount of time they spent in playing through the 9 levels were (in minutes): 17.14 (avg), 5.86 (SD). All of the 10 people finished the 9 levels. None of them showed or expressed simulator sickness.

With the video footage and observational notes, which recorded their live interactions using the system, and the audio clips for the semi-structured interviews, we conducted inductive, qualitative data analysis. Several themes emerged and were grouped. We present those themes below, with coverage of how the participants used their bodies during their involvement in the study.

Spatial Strategies: Akin but Unique

Overall, a typical, representative spatial strategy for solving the puzzles can be illustrated as: A participant starts with GV, looking around to identify the positions of the 2 gaps on the fences, and his character's location in relation to the gaps. He, carrying the memory about the gaps' locations, switches to AV, in which he can see his ground character's location (the "you-icon") and the horse. In this mode, he moves the 2 physical blocks with the spatial memory he has about the fence gaps so that he can incrementally align the gaps, with the goal of creating a pathway between the horse and the ground character. Since per our design, he cannot see where the gaps are in AV, he has to switch back to GV to see how much each gap has moved. Going back to GV from AV also solidifies (refreshes) his understanding about where the horse is. He does such switching back and forth iteratively until the gaps are aligned to allow the horse pass through, solving the current puzzle.

Although the participants had a similar overall strategy, they developed different techniques along the way. For example, some started with moving the front fence so it is aligned with the ground character, while others moved the back fence first to align with the horse. Some made big block movements early in a puzzle, then moved them slowly with small increments to "fine-tune"; others used small block movements all along. At one point, a participant used a form of "spatial spamming": since levels with randomizing, alternating aerial views were more difficult, that participant kept switching rapidly between GV and AV until she stopped at a particular AV in which the spatial information gathered during the last time that view was entered could be directly reused.

Gestures & Verbalization

Several participants (6 out of the 9 recorded users – one user requested to not be videotaped, so that person's interaction was documented with note-taking and observation only) used gestures or verbalized when solving the puzzles. The gestures included: lifting a hand from a block then using the index finger (or the whole hand) to point to a certain direction (to help them remember the horse's position relative to the ground character); titling their heads (especially in levels with multiple, randomizing AVs) to help them better "reuse" the spatial information from the last presented AV; rotating the whole body to see the surrounding objects better in GV. Rotating the whole body (and the head) became much more common starting from Level 7 because without the you-icon in AV, participants had to identify where they were originally positioned in GV using other navigation helps (e.g., the windmill is to the far right, the house is to the front-left). They carried that information to AV where they moved the blocks accordingly. Three participants even kept rotating their bodies for 180 degrees (to the right or the left) all the way from Level 7 to Level 9, which was an indication that they tried to understand the surrounding better with the aid of bodily movement (and not just turning the head).

Five (of the 9) recorded participants verbalized at least during 2 levels. Their words related to spatial relations included: "So, he [the horse] is over there, and I am right here.", "Wait, where did it [a fence's gap] go?", "Okay, the bush is to my right....", "That [block movement] was an overkill." Verbalization was often used in conjunction with gestures. Four of the 5 verbalizing participants were female. One female participant even verbalized in every level.

Although a further comparison is needed, it is reasonable to say for now that the TASC system did encourage the users to involve (more of) their bodies (gestures, movements, and verbalization), which fulfills certain design goals we set out to achieve.

Positive Experience

All participants shared positive thoughts about their TASC experience. In the interviews, they described it as “immersive”, “engaging”, “fun”, “interesting”, “rewarding”, or “never played something like it before!”. They particularly liked how their VR interactions could be coupled with physical blocks, which was something new to many of them.

Every participant agreed that TASC could be a good training tool – an immersive and aesthetically pleasing environment which can encourage users to exercise or improve perspective talking spatial ability. Two of them added that TASC would be very liked among their age group (undergraduate students). Another one mentioned that TASC could be used for kids at a younger age, “It might help them draw those [neurological] connections”.

However, they also pointed out an issue that slightly distracted their puzzle solving. While several participants said having growing difficulty levels was a good feature, for some, the levels with multiple AVs were seen as “difficult” or “frustrating”. Also, the Leap Motion was not always stable in tracking hands when the hands were in contact with the blocks for too long (e.g., when a person was thinking about how to proceed while putting her hands on the blocks). This detection instability resulted in undesired virtual hand presentations (e.g., only 1 hand or 3 virtual hands was/were rendered), which were noted as a distraction.

DISCUSSION

A System with Potential

From the demographic questionnaires, it was obvious that by far most participants had little to no experience with VR (averaging 1.9 out of our 5-point VR experience scale). Therefore, solving spatial puzzles with a VR-TEI interface was a novel experience to most of them. Their feedback shows however that it was not only enjoyable but that it activated their sensorimotor system on multiple levels. Participants used their bodies as well and verbalized their spatial thinking and perception during the interaction and without prompt. Some of these effects can be observed in other game design situations, e.g., players move their heads in games to avoid virtual “bullets” shot at them. But the multi-layered effect and the self-reflection of players noting the educational value of the system indicate that the TASC system provides effective and novel embodiment.

Other Cognitive Research Opportunities

To solve the spatial puzzles in TASC, a user needs to constantly switch between Ground View (GV) and Aerial View (AV). Although the spatial information in both views can be used to solve a puzzle, the main distinction between GV and AV is that the former is a “solution progress view” and the latter is the “action view”. This leads to the potential that, with video recording, interviews, and data logging (about when/how a user switches perspectives), the TASC system can be used to study spatial strategy differences (such as the use epistemic vs. pragmatic actions [1]) when perspective taking ability is engaged with the facilitation of embodiment.

We conducted both formative evaluation (during the design process) and summative evaluation (pilot and formal studies). By “formal” evaluation study, we mean the protocol was structured and consistent across the participants. Hence, it was not a “comprehensive” evaluation, per se, because we believe the system can be extended as a platform to study the role of embodiment in spatial cognition, and the individual differences in spatial problem solving strategies. Also, since many perspective taking ability tests are available, one immediate next step for this research would be to investigate how TASC can be used as an intervention to improve this spatial ability (at least for the short term) using a pre- and post-test evaluation protocol. To understand which factor enhances perspective taking ability more, the study can even be conducted with different conditions, e.g., one group uses the full TASC system, one group plays the same game by using only keyboard/mouse, and other intermediate conditions.

CONCLUSION & FUTURE WORK

We presented TASC, a VR-TEI system aimed to support spatial perspective ability by establishing embodiment with head/hand-tracking, tangible interaction, and virtual environment. We demonstrated our participatory and iterative design process, which led to design lessons learned from intermediary prototypes, and the final system. The final system incorporated virtual and tangible interaction, along with spatial design features to engage perspective taking ability, while keeping the system challenging and interesting. Our formal evaluation showed that overall the users had a positive experience and involved their bodies when solving the spatial puzzles with TASC.

Our short-term next step will be to investigate if TASC, as an intervention, can improve perspective taking ability or influence problem solving behaviors. This may involve conducting the study with different conditions – variations of TASC with different levels of tangibility and embodiment. For longer-term future work, we plan to collaborate with education specialists to see how the system and our design experience can be integrated with STEM curriculum.

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