Keep the Ball Rolling: Designing Game-Based Tangible VR for Spatial Penetrative Thinking Ability

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ABSTRACT
Spatial abilities are grounded in the way we interact with and understand the world through our physical body. However, existing spatial ability training materials are largely paper- or screen-based; they rarely engage or encourage the use of the body. Tangible and Virtual Reality (VR) technologies provide opportunities to re-imagine designing for spatial ability. We present a game-based system that combines embodiment in VR with tangible interfaces, and is designed around a specific spatial ability known as penetrative thinking. This spatial ability is the capacity to imagine the internal structure of objects based on external cues. This ability is important in areas like design, geosciences, medicine, and engineering. We describe the iterative design, implementation, and testing of our system, including the user study of the final design. The user evaluation results showed that participants had positive experiences when they solved the penetrative thinking puzzles in the tangible VR system.

Author Keywords
Tangible interaction; embodied cognition; virtual reality; virtual environments; spatial ability, games.

INTRODUCTION
Spatial ability is important for learning in design and STEM (science, technology, engineering, and mathematics) fields. Large-scale and longitudinal studies have shown a strong association between spatial ability and STEM career success [35, 47]. An experienced medical doctor can quickly determine where a patient's problem area is, or accurately make a surgical incision, based on limited spatial information from diagnostic tools such as X-ray imaging.

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Analyzing spatial models from geological folds or molecular structures, and creating 3D arts, require the use of spatial abilities. To become an expert in such fields, practitioners need to gain and use many spatial reasoning skills to obtain and apply the field's semantic knowledge (domain-specific knowledge). As a consequence, it is possible that a lack of spatial abilities may lead to frustration and uncertainty in career development.

This challenge, observed and summarized by Uttal and Cohen [45], illustrates the cross-disciplinary importance of spatial intelligence and spatial reasoning, namely the ability to "generate, retain, retrieve, and transform well-structured visual images" [6]. Even though spatial cognition theories relate these abilities to body-related characteristics [27, 34], many current spatial ability tests and training materials remain surface-based using 2D tools (pen and paper; digital flat displays). While those materials are well-tested by cognitive scientists (showing their validity in examining and improving certain aspects of spatial ability), they do not optimize the engagement of a user's body and purposeful multi-dimensional actions. Humans learn and gather spatial information to interact with objects, people, and environments through their bodies and actions in the world. Based on these tenets, our underlying research question is as follows: *How can we utilize emerging technologies to build interfaces that involve more use of the body and related actions, to engage spatial reasoning / intelligence?* This paper will describe one sample project addressing specific design challenges within that question.

Recent research in embodied and ideomotor theories of cognition provides a theoretical groundwork to link engagement of the body, action, and spatial cognition. This theoretical groundwork can inspire many new interaction designs [32]. However, to date, very few interfaces have been built specifically to target spatial abilities. Work on the corresponding design process and interface evaluation is even more scarce. Yet, Virtual Reality (VR) and tangible interaction design provide opportunities to address this challenge. VR can provide spatial experiences and perspectives that are difficult to achieve in the real world, and can also help to focus the user's attention and reduce external distractions. These advantages support the use of VR as an immersive technology for spatial training. In parallel, tangible interaction design focuses on embodied interaction, which is relevant for the necessary spatial reasoning activity.

Using tangibles and VR technology, TASC (Tangibles for Augmenting Spatial Cognition) is a TEI (Tangible and Embodied Interaction) system that was designed to support and engage perspective taking ability (also known as spatial orientation) [8]. The system was shown to lead to a statistically significant improvement in perspective taking abilities, whereas less action-centered keyboard interaction design and a control intervention did not [7]. Earlier work on Embodied Digital Creativity (BDC) used different ways to engage the body. This system required users to wear and use a tangible exoskeleton to perform digital tasks displayed on a wall. Again, the study found that the group using the exoskeleton system showed significant improvement in a mental rotation task, whereas other groups using conventional controls did not [36].

Inspired by TASC (designed for perspective taking ability) and BDC (designed for mental rotation), the present paper reports the design process and formative evaluations of a TEI interface designed around another spatial ability: penetrative thinking, the ability to imagine 2D cross-sections of an object using external 3D information. In the present paper we: (1) Describe the significance of studying penetrative thinking ability using a TEI interface; (2) Summarize the design processes; and (3) Report results from the implementation and evaluation of the prototypes through our iterative design cycles.

BACKGROUND & RELATED WORK

We begin by briefly introducing underlying theories in spatial cognition and embodied cognition. Here, we also provide a review of penetrative thinking, and conclude with a review of projects most relevant to our design.

Spatial Cognition

We live in a spatial world. As Newcombe and Shipley note, “a world without space is literally inconceivable” [38]. Gathering, understanding, and using information about space is crucial, if not fundamental, to how we interact with objects and environments. Eliot [15] described spatial functioning as “pervasive” – a cognitive process that is needed almost everywhere and all the time. There has been a significant amount of research on spatial cognition, and corresponding development of assessment materials for different kinds of spatial skills, such as mental rotation [39, 44] or perspective taking [18, 23, 26]. Importantly, it has been shown that spatial skills can be improved through training [46]. Spatial cognition researchers have also made attempts to categorize different kinds of spatial skills to better understand when and how they are used [38].

Spatial cognition has been researched from many different perspectives, including some that are body-based. For example, spatial scales can be categorized as figural, vista, and environment [27]. Those scales are devised as body-based relationships: within hand’s and arm’s reach (figural); observable with eye sight (vista); traversable areas (environment). Solving spatial tasks within these categories can be categorized as epistemic or pragmatic. Kirsh et al. described the difference using the video game *Tetris* [33]. Epistemic *Tetris* players tended to give more exploratory and un-intentional rotations and translations to a falling piece to better find a fitting gap. Pragmatic players mentally rotated a falling piece first before using the game controller to move the piece accordingly. Their study showed that epistemic players were more performant in the game. This finding supported later research about the role of the body for designing for spatial cognition [32].

Embodied Cognition & Common Coding Theories

Embodied cognition has become a steady reference point for interaction design [13, 37]. The theory provides a view of the body and actions not just as a form of input and output of the mind, but rather as intricately involved in perception, reasoning, and decision-making processes [48]. Robbins and Aydede [42] describe embodied cognition as “embeddedness of the brain in the body”. Hence, the notion of embodiment and how one might engage more of the body to activate certain cognitive processing has been a foundation for our interface design. A representational account which we have likewise leveraged for this work is Common Coding (Ideomotor) Theory. This theory is based on the notion that there are tight linkages connecting features across action, perception, and cognition systems [28, 29, 40]. The action system is not simply a passive receiver of information, but is an active contributor to perception and cognition. This linkage can be activated in a two-way manner, e.g., what one perceives and decides leads to certain actions, and what one does using motor skills can also influence or even improve certain cognitive processes. As a result, moving during training may enhance the learning of spatial skills.

Penetrative Thinking (Visual Penetrative Ability)

Here we provide a primer and a review of penetrative thinking. Compared to other spatial abilities that have been studied for half or even a century, penetrative thinking is a relatively new field of research. In 1996, Kali and Orion found this spatial ability while conducting a spatial learning study with geology majors [30]. Kali and Orion then coined the term VPA (visual penetrative ability) [30], which was later modified to a new term, commonly agreed as “penetrative thinking”. Kali and Orion [30], Cohen and Hegarty [11], Alles and Riggs [1], all provided their subsequent definitions for penetrative thinking. Overall, this ability is defined as the spatial ability to imagine a 2D cross-section at a certain location of an object based on its external 3D information.

Penetrative thinking has been shown to be independent from other spatial abilities such as mental rotation [25, 41].

This independence shows the need to study or design for penetrative thinking separate from other spatial abilities. Similar to other spatial skills, penetrative thinking is malleable [2, 46], meaning that there is potential to enhance this skill. Penetrative thinking has mainly been studied in geology and earth science [1, 2, 20, 21, 30] (e.g. mineralogy, sedimentology, and tectonics). At the same time, imagining cross-sectional information and using related spatial skills (e.g., penetrative thinking) is also important for medical and biological domains (e.g., dental science, human anatomy, medical imaging, and surgery), arts and design (architecture, 3D modeling), and engineering (mechanical and civil engineering) [24, 25, 31].

Importantly, Atit, Gagnier, and Shipley's work [2] showed that penetrative thinking seems to relate to bodily engagement. They compared a gesture-enabled student group with non-gesture enabled conditions and tested both with the Geologic Block Cross-Sectioning Test [2]. Results showed an increased performance in penetrative thinking tasks among the gesture-enabled participants. This result indicates that the use of gesture has a significant effect on this spatial ability and invites the use of embodied interaction design. Atit et al.'s work did not center on TEI or HCI (human-computer interaction), nor did it use theoretical support from embodiment. But these findings, along with other aforementioned literature, support our motivations to design an embodied interface focusing on penetrative thinking.

Experimentally, the Santa Barbara Solids Test (SBST) [10–12] is often used to assess the generalized form of penetrative thinking. The SBST is a 30-question paper-based test. Each question has an image of a 3D object intersected by a plane at a certain angle and position. Four choices are available in each question, and the test-taker must select the correct cross-section the plane creates as it intersects with the object (see Fig. 1). All SBST questions' objects and cutting planes are different. However, across all questions, the planes' rotations differ against the same axis.

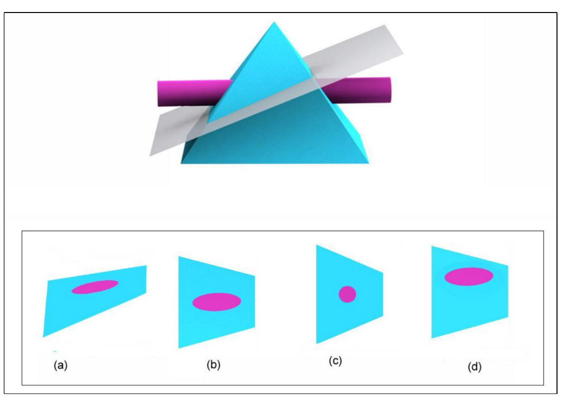

Figure 1. A question from paper-based SBST [9, 10] **(reproduced with permission): Choose the correct cross-section intersected by the cutting plane. The correct answer is (b).**

TEI for Spatial Ability

Leveraging embodied and common coding theories of cognition to support and improve spatial ability for STEM education is a natural design direction, but it has not been well studied or explored in Tangible and Embodied Interaction (TEI) design. In one study, Dünser et al. [14] studied how VR and AR (Augmented Reality) could be a training tool for spatial ability, but their research did not include tangible components. The same applies to a study using 3D virtual models as an intervention for penetrative thinking [12]. Studying its effect on spatial ability, Barrett and Hegarty [3] included a tangible device for interacting with STEM-related 3D models. The study remained an experiment, and did not provide future design implications for building an engaging and immersive experience.

The aforementioned BDC [36] and TASC [7, 8] projects are our main inspirations. Both use embodiment and tangible interfaces, but differ in their design directions. BDC used a virtual game displayed on a wall-sized screen, controlled by a body-worn tangible controller. Coupled with tangible blocks, TASC used a VR HMD (Head-Mounted Display) and hand tracking (with Leap Motion) to enhance embodiment and the immersive experience of the user. These design processes, qualitative results, and experimental analysis showed positive feedback as well as positive effects on spatial abilities among college students.

In summary, our literature review revealed the importance of studying penetrative thinking and strategies to improve this spatial ability. The discussion of related projects highlights the value of TEI design for spatial thinking, but also shows a lack of reported design processes and systems for these goals, and the need to optimize these designs.

DESIGN PROCESS: OVERVIEW

Following the conclusions of our literature review, we set out to build a tangible VR system to engage penetrative thinking with the following 3 overarching goals which are mainly inspired by the following features of TASC's design [8]: (1) The system should involve the user's body and actions with a more direct spatial sensorimotor translation, at least compared to pen/paper or other conventional input devices; (2) The system should actively require the user to apply penetrative thinking; (3) The virtual content, controlled by the tangible, should be appealing, interesting, and immersive to the users. We did not target specific domain knowledge (such as geological formations), so the content should be easy and basic to grasp to most users and potentially generalizable to many fields of science and engineering. Based on these design goals and motivated by the literature and projects described above, we decided to build a VR world with tangible interaction inputs, in which a series of spatial puzzles could only be solved using one's penetrative thinking ability. The design evolved through several iterations. Below we report on the design process and rationale of our first prototype, "Free the Birds", as well as our final version, "Keep the Ball Rolling."

FIRST PROTOTYPE: "FREE THE BIRDS"

Process: Game Design Meets Tangible VR

The design process of the project, "Free the Birds," was inspired by an iterative game design approach by Fullerton [19], with our goal to develop an engaging virtual environment on the one hand, and a tangible interaction with its spatial challenges on the other. This first generation was meant to be prototypical (and purposefully not fully-fledged) for us to identify opportunities and challenges for designing a tangible VR game around penetrative thinking.

The researchers worked with 3 students (one graduate student, 2 undergraduates) taking an embodied media design course instructed by a professor in this research team. The researchers and the students had regular design brainstorming and sketching sessions for around 4 weeks (each week for around 4 hours, due the students' availability). Then, mentored by the researchers for another 4 weeks, the students learned and applied certain software and hardware skills to iteratively build and critique prototypes from the team's ideation. This design process gave the students a hands-on experience in conducting design within the context of research.

The Virtual Environment & Gameplay

Several ideas were sketched, discussed, and expanded. From those initial ideas, the team chose and implemented the "Free the Birds" idea because of its potential to develop tangible VR for engaging penetrative thinking. This first implemented generation is a virtual environment (VE) built with Unity 3D, C#, and using free 3D assets. Users see the VE through an Oculus Rift DK2 HMD and encounter a series of spatial puzzles that follow a simple gameplay using a custom-built tangible interface. The user has to solve one puzzle to advance to the next one. The rationale for this VR game-based design are as follows: (1) Reinforcing 3D perception of objects provides better visual stimuli for penetrative thinking ability [12]; (2) Compared to displaying content on a flat screen, a VR HMD provides better embodiment and immersion thanks to head-tracking, and by decoupling from "visual noise" in the physical world; and, (3) Gameplay serves as motivation and provides a sense of fun and progression.

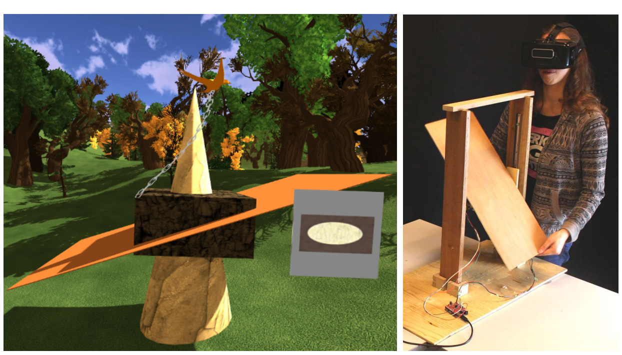

Figure 2. A puzzle in "Free the Birds": A bird is chained to a 3D object, a cone piercing a block (left); The tangible board interface (right).

Each puzzle in "Free the Birds" is a 3D object intersected by a virtual plane. This design feature was directly inspired by the Santa Barbara Solids Test (SBST) [9, 10]. But in contrast to that test set up, our design is more game-based and wraps the spatial reasoning into a playful set up. Players are asked to free a bird (see Fig. 2, left, top) that is chained to an abstract anchoring structure. Only the right cut through this structure, presented to the right in Fig. 2, will free the bird and lead to the next puzzle. This cut has to be performed using a tangible board-like interface that controls a corresponding virtual cutting plane. The design focuses players' attention on achieving this task – yet inherently utilizes the logic similar but reversed to SBST.

Our game design provides a cross-section as a fixed "target solution" for each level (a puzzle). The user has to use penetrative thinking to determine the level and orientation of the cutting plane which would lead to the solution, move and rotate the tangible board (hence, the corresponding virtual plane) with the goal of making the plane intersect with the object in a way that corresponds to the target solution, and, finally, submit their answer. This process means the game is played in a "reversed" way compared to SBST. The SBST shows a cutting plane and the objects being cut, and the test-taker is left to determine which of the 4 choices best matched the resulting cross-section, whereas our game design provides the target solution for each level, and asks the user to manipulate the cutting plane to find a cross-section that may match the target solution. We believe, instead of recreating multiple-choice questions in VR, this design is a better use of embodiment and the explorative freedom supports richness in the VR interaction. (Note: Oculus Rift DK2 tracks head movements, but does not track the user's position change.) For each puzzle, users can have as many attempts as they want. There is no time limit, nor a limited number of trials. Inspired by the SBST and its use in studies [10, 11], each puzzle in "Free the Birds" has a different level of spatial difficulty, from a singular shape to compound shapes that might have sub-shapes embedded or stacked together. Figure 2 is an embedded shape example. This first instance of the project features 4 different levels.

Designing the Tangible

The tangible interface (Fig. 2, right) was inspired by the TASC design [8] as well as the logic of the SBST. Since penetrative thinking is about imagining spatial information based on a cutting plane or a cross-section, it was reasonable to design a tangible interface around the idea of physically manipulating a plane to activate and enhance related embodiment. The tangible mechanism we built was a thin board of 27x65 cm in dimension, wide enough to involve sufficient arm movement and narrow enough that handling it would not result in fatigue or awkwardness. The physical board controls the virtual plane in each game level and maps directly on the movements of the virtual cutting plane. The board and associated control unit allowed clockwise/counter-clockwise rotation, and vertical (up and down movement. This design is inspired by the positioning of the cutting plane in the SBST, where the plane is shown cutting across the object from side-to-side. The tangible interface re-creates this arrangement by allowing the user to tilt the board from side-to-side to achieve different angles. Front-to-back tilting and rotation around the vertical axis are not supported, because these extra degrees of freedom would complicate the task (e.g., by occluding the 3D object when the board is tilted forward). As for board rotation against the vertical axis, it is not relevant for the spatial problem-solving, so it was not considered. The rotation of the board features the same degrees of freedom (DOF) to SBST's cutting plane variation across the 30 questions.

The whole tangible mechanism is mounted on 2 rails, which allows the board to move linearly up-and-down. Each rail has a screw that can move with the board. Adjusting the tightness of the screws allows the board to move along the rail smoothly, while staying at the same height when released by the user. The linear movement of the board is captured by an ultrasonic distance sensor. This sensor faces down and is attached to a supporting beam. The board is attached to a rod, which connects to the frame via two sockets. The angle of the board is captured by a potentiometer, which is attached in the rotating sockets. The ultrasonic distance sensor and potentiometer are connected to an Arduino microcontroller, which sends the board's angle and vertical position to the Unity 3D-based VE to control the virtual plane in each level. This transmission is achieved using COM port connections.

Informal Evaluation of "Free the Birds"

We conducted an informal evaluation for "Free the Birds" to understand design challenges and opportunities in our iterative design process, rather than treating this generation as a final design. However, both this informal evaluation and later design's formal evaluations adhered to the research team's approved ethics protocol. In this informal evaluation, each participant was first instructed by the researcher about the gameplay and how to use the tangible mechanism. Then, the researcher helped the participant to put on the Oculus Rift headset, and the participant started solving the puzzles. If participants wanted to submit an answer after moving and tilting the board to a position, they said verbally "Submit". The researcher then pressed a submission key (spacebar) for them. The VE would detect if this submission is correct. This was achieved by implementing a pre-defined tolerance and range that defined both a certain angle and position. If the submitted answer was within that tolerance, then the cut was "similar enough" to the target solution. If a submission is deemed correct and within the pre-defined tolerance, the participant would get a "You win!" message displayed on their VR viewport. They would then be teleported to the next level. If not, the VE would give a "Try again…" message.

Overall, the informal study had 6 participants (4M/2F age 20-25 years). They all completed the 4 levels without major difficulty or simulator sickness.

Each participant was interviewed after they completed the 4 levels. The results indicate that the problem-solving game mechanics were immediately understood and engaging. Participants liked the direct, smooth, and responsive mapping between the tangible board and the virtual plane. They all expressed that it was a fresh and interesting experience for them to play a VR game as a way to think about the cross-sections. The forest environment gave them a clear aesthetic theme, which supported their immersion. However, some key issues (KIs) emerged:

***KI-1: Poorly-conveyed game narrative*:** The bird-freeing narrative was not clearly conveyed. It was not tied into the problem-solving mechanics as much as we expected. As participants mentioned, *"I didn't see the birds, I just start and work on each puzzle"*, or, *"I saw the bird…but why should it concern me?"* Meanwhile, some visual elements with an original goal of creating an immersive virtual world (e.g., the use of shadows and animated trees swaying in the wind) actually distracted the users from focusing on the bird, the chain, and a level's objective.

***KI-2: Lack of advanced visual feedback*:** In "Free the Birds", visual feedback to the user's interactions was basic. For example, the user could only rely on in-game text messages to know whether a submission was correct or not. The object in each level did not slice open per each trial cut. Also, the chain did not break and the bird did not fly away when the user got a correct cut. Most importantly, the system did not show trial "a cut", but only tested for its correctness. That means, users could not deduce from the last erroneous attempt on how to adjust the next cut. They could not see what cross-section they got from a wrong cut.

***KI-3: Absence of progression*:** One of the participants asked, *"Is the game going to be just like that – keep solving a bunch of puzzles?"* They did not mention it as a dislike, and solving spatial puzzles needs to remain a fundamental part of the gameplay in order to engage the user's penetrative thinking ability. But this feedback indicated that users expected the levels to provide a sense of progression. Doing so should keep engaging the user, while serving as a reward mechanism.

***KI-4: Need for autonomous trial submission*:** While the participants had no difficulties submitting a trial cut with a verbal cue, they mentioned that they would prefer to be able to submit each trial on their own. We had not focused on designing an interaction for submitting responses in "Free the Birds" because it was a first prototype. However, for our next design, we had to allow participants to submit responses on their own. This independence might result in fewer interruptions during the problem-solving process, which in turn could better their manual adjustments of the board.

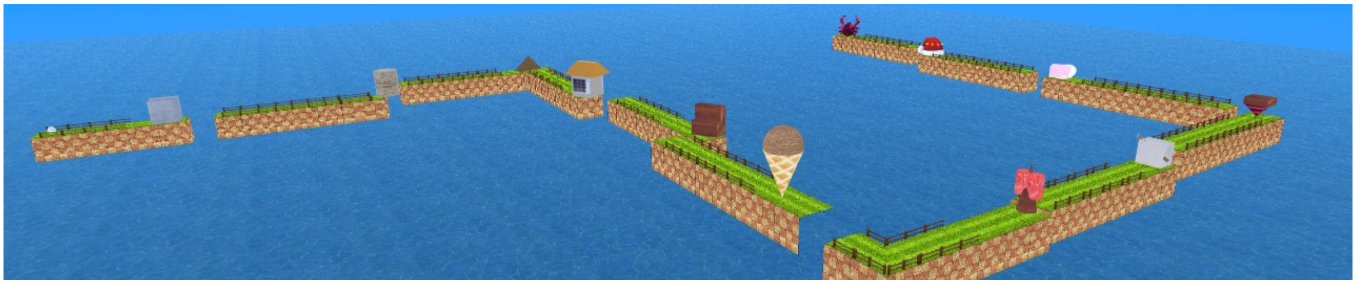

Figure 3. Course map for the final design (v1: first 9 levels; v2: all 12 levels)

FINAL DESIGN: "KEEP THE BALL ROLLING"

After "Freeing the Birds", the 3 students finished the course, while the researchers continued in quick, iterative design cycles (of ideation, implementation, evaluation, and analysis) to address the key issues described above. We focused on improvements to the virtual environment and the game's context, with some additions to the tangible interface. Following various iterative generations, we completed the design and development of the final generation, "Keep the Ball Rolling."

IMPROVED VIRTUAL ENVIRONMENT

The core gameplay of "Keep the Ball Rolling" is similar to "Free the Birds" in that it presents a series of 3D objects waiting for the user to find the correct cross-section using the virtual cutting plane. Inspired by a mini-golf course, the "Keep the Ball Rolling" VE is a single turning path surrounded by water (see Fig. 3). A ball launches at one end of the path and rolls forward until its progress is blocked by a 3D object. Players manipulate the tangible mechanism to solve the blockage by correctly cutting the object open as per the "Desired Answer" sign that continually displays the proper solution (see Fig. 4).

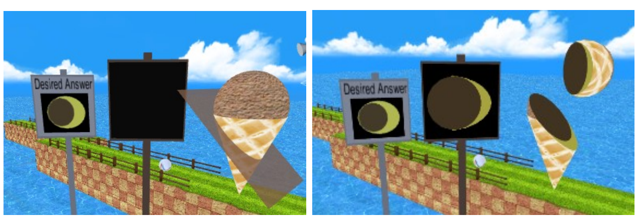

Figure 4. A level from "Keep the Ball Rolling". After a cut is made, the virtual plane disappears, the object is cut open, and the trial sign shows the cross-section per the cut.

In each level, the user sees 2 signs: the "Desired Answer" sign (solution sign, SS), and the Trial Solution sign (trial sign, TS) which is initially blank. Every time the user submits their trial per the virtual plane's position and angle, the virtual plane disappears temporarily, and the blocking object slices open into 2 sections along the cutting plane. At the same time, the just-made cross-section appears on TS. These visual effects last for 2 seconds, then the cut-open sections close back to the original object, TS returns to blank, and the virtual plane reappears. These effects reinforce the feedback of the participant's cutting activity. To support ease of use and experience, the TS is always between the object and the SS, so the user does not need to move their head too much to gather all visual information.

If cut correctly, the top part of the object disappears, and the remaining part will rotate and move to fill the gap and form a ramp between the current level's platform and the adjacent platform that leads to the next level. In that way, the cutting and objects themselves are integrated in an ongoing game situation. With the ramp in place, the ball can move forward and cross the gap to reach the next level (blockage). These game designs adjustments addressed the KIs from the previous version by providing a better game-logic for the VE. They also provide the player with a clearer purpose for cutting the object, and the object itself becomes part of the game level solution as it generates a ramp for the ball, and players can get a sense of progression.

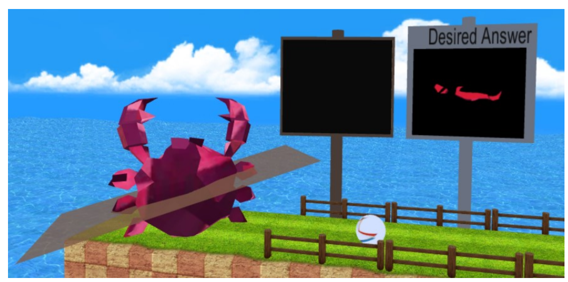

Figure 5. Level 12: a crab object from the Organic Objects set.

Consecutive game levels increase in difficulty, which is similar to the SBST's geometry that affords different levels of penetrative thinking challenge [10, 11]. We did not directly use SBST objects, rather, we designed our own objects per SBST's difficulty guideline: singular, stacked, embedded. Objects consist of simple geometry, but with a real-world reference so each level's object resembles a "real obstacle" to the ball. These design considerations led to 4 sets of 3 objects (totaling 12 objects). The 1st set has singular primary shaped objects – a cubic rock (a cube), a haystack roll (a cylinder), and a pyramid. The 2nd set features 2 stacked objects and 1 embedded object: a house (a prism on top of a block), a staircase (2 long blocks in different sizes), and an ice cream cone (a full sphere, half of it embedded in a cone; Fig. 4). The 3rd set has 1 stacked object and 2 embedded objects: a shish-kebab (a long wooden cone going through a thin block textured like meat), a tube going through a cube, and a dreidel (a thin block on top of an up-side-down pyramid). The 4th set consists of organic objects: a sprinkled donut inside a brick (a torus in a cube), a complex Santa's hat, and a crab (Fig. 5). Set 4 was inspired by Sanandaji et al.'s work [43] which studied how biological shapes could lead to more penetrative thinking challenges due to the shapes' protrusions, branches, and structures with holes. Organic shapes are not seen in SBST, but Sanandaji et al.'s research complements to SBST and aided our game design.

Small Addition to the Tangible Interface

The only notable change to the tangible interface in "Keep the Ball Rolling" was the addition of a pedal adapted from a driving game's controller set. Players use the pedal to submit a trial cut at the cutting plane's current position. Having the user press the pedal with their foot involves more of their body and avoids referencing any "outside" contribution, thus further supporting players' embodiment. This addition was based on the feedback from "Free the Birds" participants and our later iterative design cycles. An alternative solution would have been adding a button near one board-holding hand. We did not implement the button because our iterative design revealed that, with a button, the user might not maneuver the board with both hands and may be inadvertently contacted leading to unwanted selections.

Design Iterations of Keep the Ball Rolling

Following our iterative design method, we formally tested a first version (V1) of "Keep the Ball Rolling" before creating the final iteration (V2). These 2 versions were similar. While V1 may have been the final design, evaluation of V1 revealed shortcomings and led to 2 changes. Hence, we report both V1 and V2 to share our design process. The main 2 differences were: (1) V2 had all 4 sets (12 levels), whereas V1 only had the first 3 sets (9 levels). The 4th set was added because we learned from V1's formal evaluation and that the users wanted to play more levels; (2) V1's level transition involved the user's viewport following the ball, whereas the user's viewport in V2 was stationary, faded out, then teleported to the next level with fading in. This change was made because one V1 participant experienced simulator sickness, which is connected to discrepancies between perceived and actual movement in VR. V2 opted for a more static visual approach to reduce the potential for such a negative effect.

FORMAL EVALUATIONS FOR THE FINAL DESIGN

We conducted formal qualitative evaluations of "Keep the Ball Rolling" to better understand the users' interactions and experiences. Hence, these evaluations were meant to be formative to potentially prepare us for a later larger-scale study on whether or how the system can improve penetrative thinking. In these formal formative evaluations, the protocol for V1 and V2 were similar. Chronologically, we designed, implemented and evaluated V1, then implemented design changes to generate V2, which was subsequently evaluated.

Protocol

After signing the consent form, the participant was taken to the tangible interface and chose, per their preference, to use it in standing or sitting position (a high chair was provided). The researchers then gave them a brief introduction about the system and the gameplay, and helped them put on the VR HMD. During the game, participants could request a break at anytime. If they were stuck in a level, they could either ask the researchers to skip the level (controlled by the researcher via a key on the keyboard), or ask for a hint from the researcher. Hints were rarely requested. But when requests were made, the researcher verbally encouraged the participant to inspect and analyze the relationship between the 3D parts and the 2D images on SS and TS.

For each level, we programmed a tolerance in angle and position for each solution so that the user did not need to find the exact cutting angle and height. This tolerance was also implemented because finding and holding an exact position was difficult because of small movements during the gameplay when trying to maintain a stable position. Finally, the electronic signals in the tangible would have occasional jitters despite our signal smoothing function. In rare cases, even with a predetermined fixed tolerance, a provided answer that was very close to the target solution sometimes still may not be accepted by the system, being a few increments outside of the predetermined tolerance range. For situation like this, we coded another key which allowed the researcher to advance the user to the next level when the answer was visually close to the target tolerance. However, judgements to advance users through this mechanism were rare. Therefore, we believe using this human judgment was a reasonable workaround that it did not impact the research's overall validity and contribution. A refined submission judgment method may be needed for future studies aiming to more directly assess and train spatial performance.

After a 2-minute break that followed the game, the participant completed a demographics survey and an interview. The interaction with the system was video-recorded, and the interview was audio-recorded. The video camera was set up in a way that the participant's body, the tangible interface, and the computer monitor that displayed what the participant saw in VR, could all be recorded. In each system interaction session and each interview, at least 2 researchers were taking notes.

RESULTS

There were 6 participants for each iteration of "Keep the Ball Rolling" (V1 and V2). These 12 participants (3M/3F, 3M/3F) were unique, i.e., no participant used both V1 and V2, nor had any tried the earlier "Free the Birds". Participants came from different academic backgrounds. All of them were undergraduate students except for one. The age range was: 18-27 years old (mean=21; SD=2.59). The average gameplay time for V1 was 13m32s and 16m06s for V2. Every participant played through every level and finished the game. Only one participant in V2 asked the researchers to skip 2 levels because the individual could not solve 2 puzzles after many trials.

FINDINGS

While there are existing video coding methods related to spatial/tangible tasks [16, 17], these coding methods were not directly pertinent to the spatial ability of penetrative thinking with the use of a novel tangible VR interface. Hence, we used the fundamental qualitative method to analyze the videos. We generated codes from the videos per certain observed segments or elements of a participant's behaviors, e.g., "looked around with VR headset"; "rotated the plank with a big clockwise angle"; "made several fast cuts in just around 5 seconds", etc. The codes were generated from both the live notes taken during the gameplay, and the more detailed notes from watching the videos after the studies were finished. This approach presents a "bottom-up" inductive analysis to aggregate the codes into categories, then into themes [4]. The same approach was taken for the transcribed interview data.

Four themes stood out regarding how participants used the system in relation to their bodies and penetrative thinking ability. The themes are sufficient for describing both iterations (V1 and V2), and noticeable differences for the iterations will be described within certain themes.

Feedback on Embodiment-Based Controls

Overall, all participants (6 from the 9-level V1, 6 from the 12-level V2) shared positive experiences about the features designed to support embodiment: a movable tangible cutting plane for making virtual cuts, a foot pedal for answer submission, and a VR headset. When asked about using the tangible board as a controller for the VR puzzles, only one participant in V1 showed a neutral attitude, while the other 11 shared how they liked it. They described the connection between the tangible board and the virtual plane as *"responsive"*, *"smooth"*, *"accurate"*, and *"very easy to maneuver around."* These responses suggest that the board was functionally smooth and stable, and indicates that these participants had gained familiarity with the figural operation of the plane. VR was a novel experience for many participants but combining it with a tangible input was even more effective, *"I've never played anything like this, so, it was quite interesting seeing how you can integrate physical elements with a virtual game."* (V2-P3). "*I think the fun part was really just moving the thing, and having it react instead of using a…* [mouse, keyboard, etc.]" (V2-P4)

Nine of the 12 participants shared positive comments about the use of the foot pedal, noting that it involved more of their bodies without additional fatigue: *"I felt like using this was more using every part of your body than actual just sitting with one controller"* (V2-P2); "[I was] *more inclined to sort of think ahead of it more cause it's a bit more of a deliberate action. If it was a button, it would be a lot easier for me to slowly lift it* [board] *up and mash the button* [quickly]*."* (V2-P6)

In terms of using VR as a controlling/viewing device, we found that 9 participants (4 in V1, 5 in V2) moved their heads around, trying to see the environment and the object better when solving the puzzles. During the interview, some participants shared that they actually tried to lean their bodies forward, despite having been told by us beforehand that Oculus DK2 did not support movement tracking. This movement might be a sign of immersion. Four of the V1 and all of the V2 participants liked using VR. The other two in V1 did not think using VR would have made a big difference, and mentioned that maybe having a large wall-sized display might have been better. The 10 VR-liking participants described positive aspects like: immersion ("*I feel more in the game*"); novel experience; better 3D perception ("*It's highlighted in the sense that those* [3D, spatial, geometrical] *characteristics that you* [I] *might want to see are highlighted there*".

Virtual Content Design

Participants overall noticed an increase in difficulty when they progressed in the game, i.e. they expressed that later levels are harder than earlier ones. In V2, the 4th set took participants an average of 32% of the total gameplay time. This observation may be seen as an indication that the 4th set engaged more spatial problem-solving challenges.

Participants mainly relied on the 2 signs (SS, TS) when solving the puzzles. However, the opening/closing animations did give them visual cues and confirmation about their latest physical movements for using the board, e.g. *"the cut out animation tells you* [me] *exactly that, that position was cut. So…. that feedback kind of gave me an idea of if I'm going in the right direction or not."*

Since no participant tried both V1 and V2, we did not have a direct comparison between the 2 iterations. However, we see some concerns of V1 addressed in V2. As mentioned, one participant showed symptoms of simulator sickness in V1, whereas no one experienced sickness in V2. Further, although some V1 participants asked for a longer gameplay experience, no such requests were made in V2. We believe that adding more levels (set 4's 3 levels) provided sufficient challenge and fulfillment. This observation could be supported by the fact that more participants in V2 refused to take hints from the researchers, while expressing thoughts like "*Hold on* [to the hints]*, I can get this!*". The design clearly supported a goal-driven approach and motivated participants to engage.

Phases of Spatial Strategy

Although participants solved the puzzles in different ways, we describe a 3-phase model that may sufficiently encapsulate participants' spatial problem-solving strategies.

***Phase 1 (Exploration)*:** When entering a new level, a user makes several cuts to start. For some participants, the cuts seemed fast and exploratory. Other participants took time to think spatially before cutting, attempting to understand the shape with the least possible number of cuts. Either way, in this phase, the aim was to understand the relationship between the internal structure and the external geometry. *"Usually I'd look it over and try to make an educated guess on the first cuts..."* (V2-P6). *"I see what the object itself looked like to see what was going through what, and I kind of identify the shapes first. Then I looked into the reference screen* [TS, SS]*..."* (V1-P3). This phase always takes longer in levels with more complex shapes.

Phase 2 (Finding the "Key View"): The concept of key view regards a 3D object's (orthogonal) 2D projection that is enough to represent or signify the 3D object's geometry [5, 22]. We borrow the term to describe when a "representative (enough) cross-section" is found. The key view is the cross-section that starts to look similar to the geometrical semantic of the desired answer, without the acceptable dimension or aspect ratio (Fig. 6). Depending on the puzzle or the user, this phase can be short if the key view is found quickly, or an extended period because the user is not confident about the found key view or they missed the key view while making fast cuts. Phase 2 was often described as: *"Generally I would go for shape first and then size after"* (V2-P3), where finding the "shape" links to Phase 2, finding the "size" (acceptable dimension and aspect ratio) is Phase 3's goal.

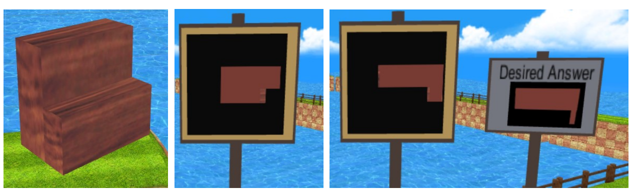

Figure 6. Phase 2: Finding the Key View. Left: The Level 5 object; Middle: A non-key view cross-section on TS (Trial Sign); Right: A key view cross-section on TS which starts to look "similar" to SS (Solution Sign, i.e., the desired answer)

Phase 3 (Fine-tuning): Every participant mentioned that after the key view was reached (whether they explicitly remembered or verbalized the Key View phase), they consciously fine-tuned their cuts to get to their chosen cross-section. Two strategies were observed. One strategy was to only adjust one factor (board height or angle) while keeping the other factor constant. Due to the object's geometry and the board's current position, this strategy might never lead to the acceptable cross-section, unless the user makes a bigger adjustment for both factors. We suspect having found the key view gave the user confidence that they do not need to fine-tune both factors. As for the other strategy, seen more in difficult levels, a few participants would keep their foot on the pedal while quickly adjusting the plank to see more frequently-updated cross-sections on TS. This "trick" may involve very limited penetrative thinking, and is similar to the "visual spamming" found in the user study for a tangible VR system designed for perspective taking ability [8].

We also observed a "reset" behavior when a participant got stuck solving a puzzle. Here, the participant would move the plank drastically, sometimes to the opposite angle or a vastly different height, then quickly move it back. We suspect these actions allowed the participant to get a new start and re-gain confidence by refreshing their understanding about the movement ranges of the plank and their body. It may also regain their dexterity by relieving possible fatigue from staying in a fixed position for too long. This reset behavior was observed sporadically in Phase 2, but appeared mostly in Phase 3.

Thinking About Penetrative Thinking

Based on observations and interviews, we argue that "Keep the Ball Rolling" succeeded in activating penetrative thinking. All but one participant finished the game by completing all levels. The single outlier had to skip 2 levels. Given the particular level design, this success rate would have not been achieved unless penetrative thinking was used. We did not mention the term or logic of penetrative thinking to participant until the post-interaction interviews, when we gave participants a quick primer about this spatial ability. All participants responded by saying they were certainly using the spatial ability during the game. One participant of V2 reported, *"I remember asking myself the question 'But what would it look like if I cut it?'."*

During the interviews, however, 11 participants could not describe whether or how this spatial ability is used in daily life or learning materials. These 11 participants needed prompts from the researchers (e.g., "the spatial ability is used for geosciences because students need to imagine inner structure of the earth") before they elaborated on how it could be used or designed for their own or other domain areas. Without our prompt, the 12th participant, a medical school student, mentioned how imagining cross-sections was important when learning human anatomy. They expressed excitement that, in addition to existing textbooks and computer-based programs, our tangible VR design would benefit medical school students.

Ultimately, the feedback showed that: (1) Our design did engage the participants' penetrative thinking with tangible and play-based interactions; (2) Consistent with existing literature, penetrative thinking is a relatively unfamiliar spatial ability in comparison to other spatial abilities like mental rotation. These results show the need and the potential to design more interfaces to support penetrative thinking, given its' importance in certain fields.

DISCUSSION

Future Design/Research Opportunities

Our user studies showed that we could externalize (or visualize) how participants used phases of penetrative thinking with respect to their bodies. This conclusion is based on how: (1) We designed a series of puzzles inspired by the SBST, a standardized penetrative thinking test whose question design was validated by cognitive scientists and used by educators; (2) We gave the participants a tangible and virtual cutting plane as an embodiment-based tool to support engagement and activate penetrative thinking through a VR- and TEI-based design. To our knowledge, such design and findings have not yet been reported.

Although our final design does not have defined spatial performance metrics, we think it is possible to extend our designs and findings toward more applied teaching of penetrative thinking ability. One aspect our design emphasizes is a theoretical grounding in common coding theory and the role of embodiment in assessing and enhancing penetrative thinking. It delivers a design space that combines tangible and virtual interfaces. Although our system involves an immersive experience, it is not clear if it leads to more "meaningful embodiment" or enhanced experiences than other approaches, and if the experience has training advantages over traditional interfaces. As a next step, we propose a comparative study with different interface conditions to test if the system can engage and improve penetrative thinking ability more than conditions that provide a lower level of embodiment, and to study how different kinds of behaviors may emerge, allowing us to further the understanding of any body-based externalization of spatial problem-solving.

Broader Societal Impact

Spatial abilities are positively correlated with achievement in STEM learning and STEM-related careers. Paper-based spatial ability tests or training materials have been used by educators for decades, with affordability as one of the reasons. Based on common coding theories that are grounded in the idea that action is tightly coupled to perception and cognition, tangible VR seems to have the potential to provide an enhanced and more flexible level of testing and training that cannot be achieved with traditional methods. VR is becoming increasingly affordable both as intervention and as assessment tool. Yet, only through the integration of significant and iterative advances in technology and the cognitive sciences will the full potential of affordable tangible VR be realized. Such affordable and flexible systems can also help to overcome the "Digital Divide", particularly in educational contexts. In addition to the value of such a system for activating spatial ability, we are argue that future extensions of this work can contribute to positive social impact beyond the context of spatial learning.

First, through our iterative and collaborative design processes, researchers and participants were all able to share feedback and engage in the design process. With both parties becoming potential stakeholders, we see valuable opportunities for co-design approaches in this novel field. Participants realized that their feedback contributed to an extended design-related discussion and informed technological implementations and iterations. Our iterative design approach indicates that participatory design may have broader potentials in using newer technologies (e.g., tangibles and VR) for research and educational purposes. Second, the items we used to build the tangible cutting mechanism were not expensive. Using low-cost electronics and material to build a novel, multimodal experience aligns with the recent Maker Movement, which has been considered to bridge the Digital Divide. Our system necessitates some costly parts, with the computer being the most expensive component. However, thanks to the newly released low-cost VR devices and accessories (e.g., Oculus Go, Google Daydream, Samsung Gear VR), and the fact that our virtual content actually does not require heavy photorealistic rendering, we think it will be reasonably affordable for interested educators as well as researchers in the field of cognitive sciences to use our research as a springboard to extend to other learning context.

Finally, we hope this discussion generates further reflections. We hope our presented design can support researchers and educators (either in spatial learning or other fields) by sharing our thoughts on how designing tangible virtual reality can potentially involve more participatory design and bridge the Digital Divide, leading to design considerations that better support embodied experiences. To further these discussions, more research needs to be conducted to expand the implications of the presented design's direct and indirect societal impacts. The work presented herein aims to trigger more discussions in such topics, within or outside of the context of spatial ability.

CONCLUSION

We have presented the design process, theoretically-driven design rationale, and evaluation for a tangible VR game designed for penetrative thinking -- a relatively newly discovered spatial ability that is important to many fields. Overall, the aim of our design is to activate and engage penetrative thinking with embodiment established by the tangible VR game. We iteratively designed two main generations. The first generation ("Free the Birds") and its informal evaluation allowed us to identify relevant design opportunities and challenges, which were summarized as Key Issues. Then, we conducted iterative design cycles, leading to the second generation "Keep the Ball Rolling", which had 2 versions with noteworthy differences. The formal evaluation of these systems yielded four themes on: (1) feedback about embodiment-based controls, (2) feedback about virtual content, (3) phases of spatial strategy, and (4) the use and perception about penetrative thinking. With the whole design process and formative evaluations, we envision future design and research opportunities, while reflecting on possible societal impacts.

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