A Tangible VR Game Designed for Spatial Penetrative Thinking Ability

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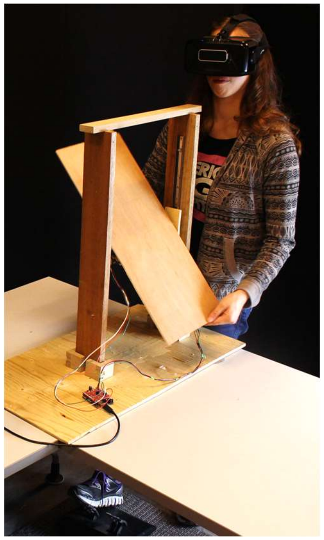

Figure 1: A user interacting with the tangible "plank" interface.

Figure 2: An example level in "Keep the Ball Rolling". Players must cut the object to match the cross-section shown on the solution panel (Desired Answer panel) in order to proceed.

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Abstract

Longitudinal and large-scale studies have shown a strong link between spatial abilities and success in STEM learning and careers. However, many spatial learning materials are either still 2D-based, or not optimized to engage students. In addition, research in spatial cognition distinguishes many spatial abilities as independent from one another. This implies the need to design content and interactions that target individual spatial abilities in order to further research and support training. Following this approach, we describe the design and implementation for a VR system, "Keep the Ball Rolling", controlled with tangible inputs and played as a multi-level game. The system is designed around one central spatial ability: penetrative thinking, which is important in geology, biology, human anatomy, and dentistry among other areas.

Author Keywords

Spatial ability; spatial cognition; virtual reality; tangible interaction; embodied cognition; games.

ACM Classification Keywords

H.5.1. Information interfaces and presentation (Artificial augmented and virtual realities)

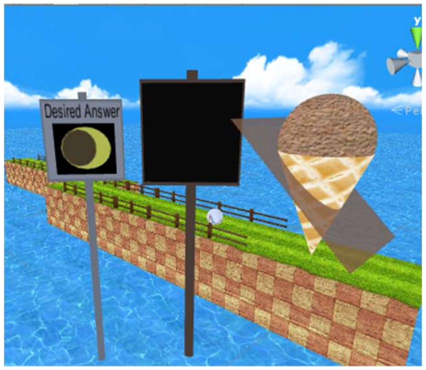

Figure 3: An unsolved level in the game.

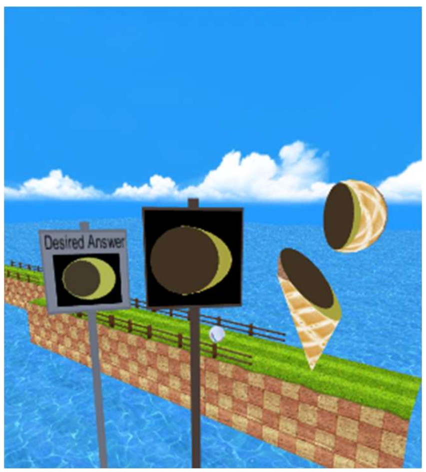

Figure 4: When a player cuts the 3D object using the tangible plank, their submitted answer is shown on the progress panel (the panel on the right side). The object also opens accordingly per the cut, then closes shortly.

Introduction

Spatial ability, the ability to gather, process, and act on spatial information, has been shown to be an important cognitive factor in many professions. For example, spatial ability is highly correlated to STEM (science, technology, engineering, and mathematics) learning and career success, per longitudinal and large-scale studies that tracked large numbers of participants over years and even decades [7]. Given the current call to advance STEM education broadly, spatial abilities stand out as a fundamental area in need of applied research to develop new STEM learning tools and approaches.

Many existing STEM learning materials and tests for spatial ability are 2D-based (used with pen & paper, computer monitor, mobile phone or tablet). They do not fully afford the 3D perception necessary for spatial problem solving in the real world. Also, those applications are often controlled with conventional input devices (e.g., keyboard/mouse, touchscreen), which do not utilize tactile and visuo-motor skills. Yet, tactile and embodied engagement are central for spatial cognition. Finally, the spatial tests and learning materials are not always designed to engage users with fun and aesthetics. Learners may lose interest quickly, which reduces the efficacy of the training materials.

We describe the design and implementation of a tangible VR (Virtual Reality) game, "Keep the Ball Rolling" that centers on the spatial ability of penetrative thinking. Penetrative thinking is the ability to imagine the interior structure of objects based on external 3D information. It is independent from other spatial abilities [3] and was originally discovered in 1996 and termed "visual penetrative ability" (VPA) [5]. Due to its late discovery, penetrative thinking lacks the depth of research found in other spatial abilities that have been studied for more than 50 years. However, penetrative thinking remains important in STEM as a general spatial ability, and as an applied ability in areas such as geology, biology, human anatomy, and dentistry [1].

The "Keep the Ball Rolling" system combines tangible inputs (a tangible plank and a foot pedal) that support physical and embodied interaction in a VR environment that features game-based interactions. The interaction design focuses on penetrative thinking because it allows participants to look at a 3D game world, which features increasingly complex spatial puzzles that can be solved with the tangible interface. These solutions require penetrative thinking, namely finding the right cross sections through the presented objects.

Related Work

Spatial ability is what characterizes spatial cognition, a mental process that is often studied in correlation to the body [4]. Embodied cognition, a branch of the cognitive sciences, provides a lens to view this body-mind linkage. It studies how the body and action shape one's perception. Here, the visuo-motor system is not just an input or output of the brain, but is always a part of the embodied cognitive process [8]. Hence, a system that involves the body more holistically (e.g. through movements or tangible interactions) can elicit and support more of the mind's spatial-related activities.

Interactive systems that are designed around using tangible and embodied interactions to support spatial ability exist, but often utilize the connection without directly exploring the development of the spatial ability. The present work builds on previous projects such as are emBodied Digital Creativity, a tangible exoskeleton

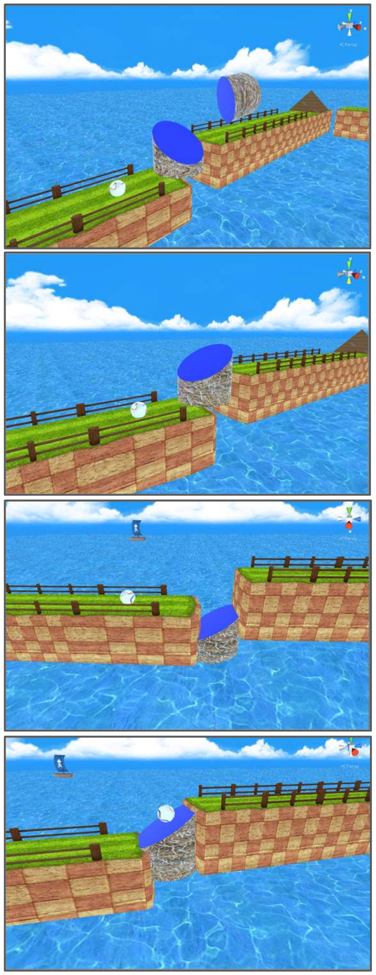

Figure 5: The bottom part of a correctly cut object forms a ramp between platforms so that the rolling ball can proceed.

and wall-display that improves mental rotation [6], and Tangibles for Augmenting Spatial Cognition, a tangible VR game that engages and improves perspective taking [2]. Both projects combine tangible interfaces and virtual environments with spatial cognition, but neither focuses on penetrative thinking.

Design & Implementation of the System

This project builds on the authors' earlier work on perspective taking in the TASC project [2] but differs in its design focus on penetrative thinking. With this focus in mind, the design rationale of the system was to: (1) provide an interface that supports high levels of embodiment through VR visualization and tangible interaction; (2) engage participants through game-based content to support extended interest; and (3) include evaluation tools to assess users' performance.

The implementation combines a VR visualization with a tangible interface in a 3D game environment. Players enter a game world that features a series of platforms floating on water. A ball rolls automatically along each platform, but at the end of each platform a 3D object blocks its way. This 3D object is a spatial puzzle that the user must solve in order to allow the ball to continue along its course. Players must cut the object to match a given cross-section. When cut correctly, the object forms a ramp to the next platform. Players operate a tangible plank as a cutting device. This plank was created as a tangible interface that directly affects the position and orientation of a virtual plank, which serves as a cutting plane in the VR world. Whenever a player believes that the chosen cut would produce the required cross-section, they press a foot pedal that triggers a virtual cut of the object. The upper part of the object is detached along the virtual plank and the cross-section image is shown on a progress panel. If the player operates the plank in such a way that it cuts the virtual object at the correct cross-section, the puzzle will be solved and the ball continues to roll along the next platform toward the next puzzle level.

Players have to project the internal cross-section of each object and match it to their interactions. These interactions are designed to emphasize embodiment through perspective (VR visualization) and tangible input (the physical plank and the foot pedal). Our design for each level was inspired by the research from Cohen and Hegarty [3], who proposed and evaluated a spatial ability test for penetrative thinking called the "Santa Barbara Solids Test" (SBST). The game levels increase in difficulty similar to the SBST, from simple to joined to embedded geometric objects, and finally to organic objects.

"Keep the Ball Rolling" was implemented in Unity 3D. The player sees the virtual environment with a VR headset (Oculus Rift) and interacts with a physical plank mounted on two rails that can move up and down and tilt side-to-side. The up/down movements of the plank are captured by an ultrasonic distance sensor, while the side-to-side tilting movements are captured by a potentiometer. These sensors connected to an Arduino microcontroller and the board's movements are thus mapped onto the movements of the virtual plank in Unity 3D. As the system was implemented as a test bed for penetrative thinking, it tracks a range of player interactions: the number of cuts made, the timing of each cut along with its angle and vertical position, as well as the difference between each cut made (angle and vertical position) and the actual solution. This data is automatically recorded and stored after each session.

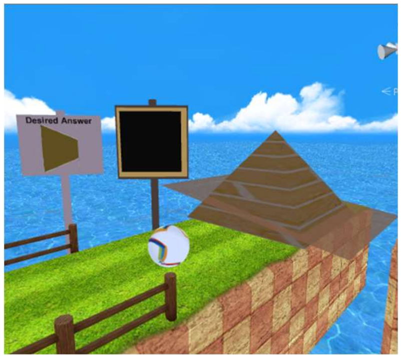

Figure 6: Game Level 3 is a Pyramid, from the Simple Objects set.

Figure 7: Game Level 12 is a crab, from the Organic Bbjects set.

Conclusion & Future Work

"Keep the Ball Rolling" addresses a pressing challenge: supporting spatial abilities through novel applied research based on cognitive sciences, which has the potential to advance STEM education. It presents a unique design and implementation that combines VR with tangible interfaces in a game that is optimized for the targeted penetrative thinking spatial ability. Ultimately, it provides the necessary prototype allowing us to evaluate the interaction design and the effects of these adjustments on the spatial abilities of the users. Currently, we are conducting these tests.

Going forward, we consider other possible spatial abilities and designs to engage them in effective ways. Based on our past work and the current initial evaluation of this system, this research promises to be impactful not only for interaction design but also for cognitive sciences through the development of new forms of targeted user engagement and assessment.

Acknowledgements

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