The Design and Evaluation of Embodied Interfaces for Supporting Spatial Ability

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ABSTRACT
Shown in many longitudinal studies, spatial ability is important to learning and career success. This paper, inspired by [2,14], presents the new generation of TASC (Tangibles for Augmenting Spatial Cognition) to illustrate how (re)design lessons can be learned, how existing evaluation methods can be applied, and how new evaluations may be generated or envisioned, when a TEI (tangible and embodied interaction) system is built to study spatial ability.

Author Keywords
Embodied cognition; tangible interaction; virtual environment; spatial cognition; spatial ability; game; STEM

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Spatial cognition is about how we retrieve, organize, and use spatial information in relation to the environments. The ability to process and apply spatial information is vital to our daily lives. Such ability is characterized or defined as spatial ability. In many professions, spatial ability has been shown as an important cognitive factor. For example, the United States' 2012 Report to the President [15] asked for one million additional STEM (science, technology, engineering, and mathematics) graduates to meet the increasing demand from the workforce. This reinforced the importance of spatial ability, as many longitudinal studies showed that spatial ability is highly associated with STEM learning and career success. Selected longitudinal studies are: 1) Study of Mathematically Precocious Youth (SMPY) [13], which followed more than 5,000 academically performant students for 35 years starting from 1971. This study showed that spatial ability strongly links to success in STEM fields; 2) In 2009, Wai et al. [16] examined 50 years of research, with samples extracted from 400,000 participants who were tracked for at least 11 years. Wai's results were coherent with those from SMPY's, and indicated that spatial ability can be a strong predictor of STEM performance.

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Understanding and manipulating spatial information is also important for interaction design. Many TEI/HCI (human-computer interaction) systems are unified together with seminal design frameworks, which contain spatial-related themes. For instance, the RBI (Reality-Based Interaction) framework [10] analyses and consolidates interaction styles with the themes of *Environment Awareness and Skills* (for spatial information related to objects and environments), Naïve Physics, Body Awareness and Skills, and Social Awareness and Skills. Hornecker's framework [9] also enumerates the elements for tangible interaction: *Spatial Interaction*, Tangible Manipulation, Embodied Facilitation, and Expressive Representation.

While spatial ability is important, and the use of the ability is common in TEI systems, these following observations are the motivations (M1 to M3) that drive this research.

M1. Need to "get to the bottom" of it more: Not many studies focus on how TEI systems can directly influence spatial ability even though spatial manipulation is a common theme in TEI/HCI. Of the few TEI-related we find and include here are BDC (emBodied Digital Creativity [14]) and TASC's prototypical/conceptual 1st generation (Gen1) [2]. Meanwhile, spatial ability studied in cognitive science has involved the role of the body (egocentric vs. allocentric [12]; figural, vista, or environmental [6]), while TEI often includes the body and its movements in the interactions. Therefore, with those 2 sub-observations (few TEI systems directly study spatial ability; the body does play a role in spatial ability), we believe there are potentials to understand *more* about the effects of TEI on spatial ability.

M2. Spatial ability-specific TEI system: Findings from cognitive science have shown that spatial abilities are independent from one another. For example, perspective taking ability (spatial orientation) is not directly correlated to mental rotation [7]. Therefore, extending M1, a TEI system designed for supporting spatial ability research should target a particular spatial ability. This is also something mentioned/inspired by the design framework proposed by Clifton et al. [2].

M3. Where is the "space" in "spatial"?: Many spatial ability tests or training materials are surface-based: administered with paper, or digitized then provided with computer monitors. We are not questioning the validity of those tests or training materials because they are indeed well-developed and widely-used in many fields. But with the rising availability of VR which affords 3D perception, it is certainly worth exploring the notion of "putting space (3D perception) back to spatial (spatial tests or training materials)". Extending from this idea, new design and evaluations that put emphasis on the body (movements in physical 3D space; engaging visuo-motor skills with tangible objects) should promise research potentials.

With those motivations, we envision this work to contribute to the (re)design and evaluation for embodied interfaces built to support and improve spatial ability.

RELATED WORK

In this section, selected projects in the literature are analyzed, along with certain aspects of their application and limitation to this research.

Common Coding Theory & Spatial Ability

BDC [14] is among the few studies that investigate the effect of TEI on spatial ability (mental rotation), which is also one of the inspirations to this study. It is based on a branch of embodied cognition, "common coding theory" (ideomotor theory) [8], which claims that there are mental common codes that link perception, cognition, and action. Such links can be activated by multiple modalities of input, as well as when self-movement is recognized. BDC built a wearable exoskeleton (the puppet) which captures and displays the user's full-body movements onto a 3D avatar. A user performs rotation-based spatial tasks with the avatar by controlling the puppet. With spatial pre/post-tests, the result showed that users with the TEI condition (the puppet) had more improvement in mental rotation ability than other conditions that had less embodiment and tangibility (e.g., keyboard, XBox gamepad). BDC is about designing a TEI system to immerse users and engage their spatial ability. TASC Gen1 started with the question "how can another spatial ability (perspective taking) be studied through the lens of TEI?".

Design Framework

Very recently Clifton published his design framework [2], which is arguably the first one to systematically connect TEI design and spatial cognition. This framework analyses TEI systems in a design space populated by three dimensions with subcategories of: Aspects of Spatial Cognition, Embodiment, and Intervention. Throughout the course of this research, we will generate design lessons learned then compare them with this framework. The goal is to see if/how new design opportunities emerge by comparing the framework with the iterative (re)design process, and how generation(s) of TASC differ in design and evaluation.

Evaluation Methods

In terms of evaluation, we are not very concerned about evaluating a novel TEI system's usability or aesthetics with common approaches such as usability heuristics or interface criticism methods. We are interested in the power and limitation of 2D spatial ability tests for 3D based TEI system, and how to develop new spatial ability evaluations from a TEI (re)design experience.

While there are many (2D, paper-based) spatial ability tests, and they can be found on the NSF (of the US)-supported SILC website (Spatial Intelligence and Learning Center), it is worth noting that there is very little work that considers how to code, analyze, and classify spatial activities and strategies when TEI is involved. Among the few found, the most relevant are: Antle and Wang [1] compared spatial strategies using motor-cognitive skills between tangible and multi-touch interface users. Esteves et al. [3] provided a video coding method with 20 epistemic actions (actions that are not made directly for the goal, but are trial and errors that can reduce work complexity). They later expanded the method as the ATB Framework (Artifact, Tool, and Body) to analyze TEI-related spatial strategies, and conducted "the evaluation of the evaluation" on the framework's reliability, validity, and predictive power. ATB has certain limitations. For example, its coding method relies much on each rater's subjective interpretation; high level of action granularity; and it's originated from hand movement analysis, so its applicability to full-body movement is yet to be validated. Also, ATB does not directly study spatial ability. However, the evaluation framework, including how it was developed and further evaluated, has inspired us to study TEI-related spatial strategies when a certain spatial ability is engaged.

RESEARCH QUESTIONS

These research questions are relevant to this work. **R1.1:** What is the iterative (re)design process for a TEI interface built to support spatial ability (TASC Gen1 to Gen2)? **R1.2:** How can that (re)design be compared to the design framework proposed in [2]? **R2.1:** What are the effects of TEI interfaces on perspective taking spatial ability? **R2.2:** How is such spatial effect different from other low- or non-TEI interfaces? **R3.1:** How to use existing evaluations for a spatial ability-based TEI system? **R3.2:** What are the new evaluation methods we can generate or envision from the said (re)design process and spatial effects?

METHOD (AN ONGOING PROJECT)

We have several ongoing projects to address those research questions. Here we briefly describe one of the projects: TASC Gen2, a newer significant version as a result from our participatory and iterative design process. TASC Gen2 establishes embodiment using virtual and tangible interactions to engage perspective taking ability, allowing the user to solve a series of virtual spatial puzzles with increasing difficulty.

Overview

TASC is a VR-TEI system designed to study perspective taking ability, a kind of spatial ability that involves imaging looking at objects or environments form different points of view. This ability is important in STEM education, or trainings for pilots and drivers.

Establishing Embodiment with VR-TEI

Based on common coding theory [8] and inspired by Malazek's BDC project [14], TASC engages spatial ability by establishing embodiment, which is achieved in three ways (Figure 1): 1) The user wears an Oculus Rift head mounted display (HMD), which tracks her head movements and provides a 3D, immersive view of the virtual environment (VE); 2) Leap Motion is attached on the HMD so that the user's hand movements can be captured and rendered as virtual hands in the VE; 3) A table with two long tangible blocks is placed in front of the user. Each block can only be moved linearly as it is constrained on 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 (described more below).

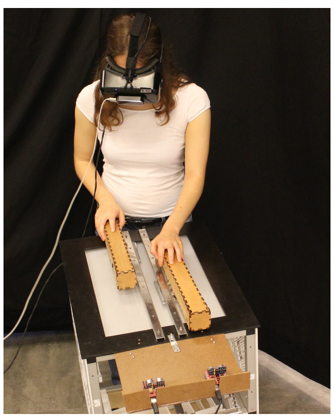

Figure 1. The physical setup of the TASC system

The VE, a game made in Unity, situates the user in a farm with structures such as a cabin, windmills, bushes, and a stack of logs. There is a standing horse whose initial position is always separated by 2 long fences from the user's ground character position. 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 to the user's ground position in the farm.

Switching Perspectives for Spatial Tasks

The user switches between two perspectives to solve a series of spatial puzzles. In GV (ground view), see Figure 2, the user sees things from on the ground. As mentioned, she is separated from the horse with two fences. With the fence design (one is taller than the other), she can see the positions of fences' openings, surrounding objects (bushes, windmill) as landmarks. However, in this view, moving the physical blocks does not reposition the virtual fences. In AV (aerial view), see Fig 3, the user looks down from above the farm as a bird's eye view. With AV, the user gets to have a holistic overlook about the spatial relationships of farm's objects (including where her GV location is). She also gets to move the virtual fences by moving the physical blocks. However, the fences' openings are hidden to her in AV. Therefore, she needs to keep switching so the incremental spatial information gained from one perspective can be applied to the other. Levels have increasing spatial difficulty, engaging and challenging them to keep using perspective ability to solve the puzzle in each level.

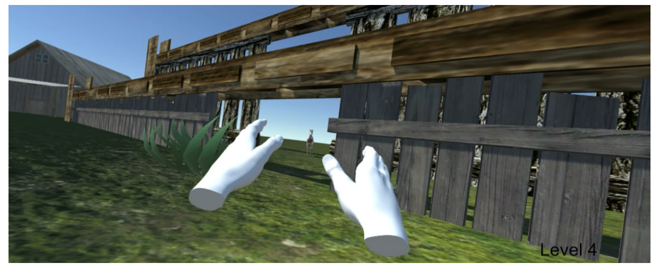

Figure 2: Ground View (the openings are aligned, the puzzle is solved, the horse runs toward the user.)

Figure 3: Aerial View (the short orange cylinder is the user's GV location)

Evaluation

The evaluation is conducted with multiple conditions of the system, each with different levels of tangibility or embodiment. For example, one condition is that the user plays the same horse-finding game on a computer with keyboard and mouse, without the HMD, Leap Motion, and tangible blocks.

The evaluation aims to answer these two main questions: 1) How does a user involve her body to solve the spatial tasks? This can be expanded to sub-questions like: What are the commonality and uniqueness of their spatial strategies? What are their problem-solving aids? How does one's perspective switching behavior change over the course of the gameplay? How can those observations be compared between interface conditions? This first question is studied with video recording, observation, note-taking, post-interaction interview, and data logging.

The second evaluation question is: 2) Does the interface engage and improve the user's perspective taking spatial ability? This is assessed form a pre/post-test intervention method: the user takes a perspective taking ability test before and after playing the game. Hegarty's team's PTSOT (Perspective Taking and Spatial Orientation Test)

[5,11] is chosen for this intervention procedure. PTSOT is not designed for children like Frick's perspective taking test is [4], so it guarantees more validity for TASC's convenience sampling with college students (mostly older than 18 years of age). The perspective taking ability change is compared among different conditions of the interface.

CONCLUSION & FUTURE WORK

In this paper, I present the study's motivations based on observations from related literature. I also list inspirational theories, projects, and design framework, along with what their application and limitation may be to the research. I describe the TASC Gen2 system, a VR-TEI interface that aims to utilize embodiment to support and improve perspective taking ability. Levels of tangibility and embodiment may yield different spatial ability performances, therefore, conditions of TASC will be used in the evaluation. The next steps include incorporating cognitive factors and VR interaction design for more levels, followed by designing and conducting the qualitative and quantitative evaluations. The findings I gather from this re-design and evaluation process, along with other ongoing projects, will help achieve the study's overarching goals of: to summarize design lessons learned, to examine/use existing evaluations, and to generate/envision new evaluations for tangible and embodied interfaces designed for supporting spatial ability.

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REFERENCES

1. Alissa N. Antle and Sijie Wang. 2013. Comparing Motor-cognitive Strategies for Spatial Problem Solving with Tangible and Multi-touch Interfaces. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (TEI '13), 65–72. https://doi.org/10.1145/2460625.2460635
2. Paul G. Clifton, Jack Shen-Kuen Chang, Georgina Yeboah, Alison Doucette, Sanjay Chandrasekharan, Michael Nitsche, Timothy Welsh, and Ali Mazalek. 2016. Design of embodied interfaces for engaging spatial cognition. *Cognitive Research: Principles and Implications* 1, 1: 24. https://doi.org/10.1186/s41235-016-0032-5
3. Augusto Esteves, Saskia Bakker, Alissa N. Antle, Aaron May, Jillian Warren, and Ian Oakley. 2014. Classifying Physical Strategies in Tangible Tasks: A Video-coding Framework for Epistemic Actions. In *Proceedings of the Extended Abstracts of the 32Nd Annual ACM Conference on Human Factors in Computing Systems* (CHI EA '14), 1843–1848. https://doi.org/10.1145/2559206.2581185
4. Andrea Frick, Wenke Möhring, and Nora S. Newcombe. 2014. Picturing perspectives: development of perspective-taking abilities in 4- to 8-year-olds. *Frontiers in Psychology* 5. https://doi.org/10.3389/fpsyg.2014.00386
5. M Hegarty, M Kozhevnikov, and D Waller. 2008. Perspective taking/spatial orientation test. *University California Santa Barbara. Retreived from: http://spatiallearning.org/resource-info/Spatial_Ability_Tests/PTSOT.pdf*.
6. Mary Hegarty, Daniel R. Montello, Anthony E. Richardson, Toru Ishikawa, and Kristin Lovelace. 2006. Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence* 34, 2: 151–176. https://doi.org/10.1016/j.intell.2005.09.005
7. Mary Hegarty and David Waller. 2004. A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence* 32, 2: 175–191. https://doi.org/10.1016/j.intell.2003.12.001
8. Bernhard Hommel, Jochen Müsseler, Gisa Aschersleben, and Wolfgang Prinz. 2001. Codes and their vicissitudes. *Behavioral and Brain Sciences* 24, 5: 910–926. https://doi.org/10.1017/S0140525X01520105
9. Eva Hornecker and Jacob Buur. 2006. Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '06), 437–446. https://doi.org/10.1145/1124772.1124838
10. Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. 2008. Reality-based Interaction: A Framework for post-WIMP Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '08), 201–210. https://doi.org/10.1145/1357054.1357089
11. Maria Kozhevnikov and Mary Hegarty. A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition* 29, 5: 745–756. https://doi.org/10.3758/BF03200477
12. Sandra C. Lozano, Bridgette Martin Hard, and Barbara Tversky. 2007. Putting action in perspective. *Cognition* 103, 3: 480–490. https://doi.org/10.1016/j.cognition.2006.04.010
13. David Lubinski and Camilla Persson Benbow. 2006. Study of Mathematically Precocious Youth After 35 Years: Uncovering Antecedents for the Development of Math-Science Expertise. *Perspectives on Psychological Science* 1, 4: 316–345. https://doi.org/10.1111/j.1745-6916.2006.00019.x
14. Ali Mazalek, Sanjay Chandrasekharan, Michael Nitsche, Tim Welsh, Paul Clifton, Andrew Quitmeyer, Firaz Peer, Friedrich Kirschner, and Dilip Athreya. 2011. I'M in the Game: Embodied Puppet Interface Improves Avatar Control. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '11), 129–136. https://doi.org/10.1145/1935701.1935727
15. Steve Olson and Donna Gerardi Riordan. 2012. *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics. Report to the President*. Executive Office of the President. Retrieved September 20, 2016 from http://eric.ed.gov/?id=ED541511
16. Jonathan Wai, David Lubinski, and Camilla P. Benbow. 2009. Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology* 101, 4: 817–835. https://doi.org/10.1037/a0016127