Embodied Spatial Cognition in Tangible Computing

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1. INTRODUCTION

We have designed Tangible Landscape – a tangible interface powered by a geographic information system (GIS) – that gives spatial data an interactive, physical form so that users can naturally feel it, see it, and shape it. Our aim was to iteratively design and empirically test a tangible interface that augments spatial thinking and improves spatial performance. Spatial thinking can be embodied – people can functionally think about space with their bodies by cognitively grasping objects and physically simulating it [Kirsh 2013]. Theoretically tangible interfaces should improve spatial performance through embodied cognition by enabling natural modes of interaction [Dourish 2001], offloading cognitive processes onto the body [Kirsh 2013], and computationally augmenting spatial thinking [Dror and Harnad 2008]. We designed Tangible Landscape to physically manifest digital data so that users can cognitively grasp the data as an extension of their bodies and automatically, immediately, and subconsciously interact with it. We conducted a series of experiments using quantitative methods including geospatial modeling, analysis, simulation, and statistics and qualitative methods including semi-structured interviews and direct observation to test whether tangible interfaces can improve spatial performance. We also explored how users approached spatial problem solving using Tangible Landscape in a serious gaming event.

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1.1. Spatial thinking and computation

Spatial thinking – 'the mental processes of representing, analyzing, and drawing inferences from spatial relations' [Uttal et al. 2013] – is used pervasively in everyday life for tasks like recognizing things, manipulating things, interacting with others, and way-finding. Spatial thinking is also used extensively in science, technology, engineering, the arts, and math for tasks like diagramming concepts, visualizing data, simulating physical processes, mapping and manipulating molecules, designing circuits, designing buildings, shaping sculpture, and studying topology. Given the importance of spatial thinking – personally, academically, and professionally – how can we effectively improve our spatial performance, our ability to perform tasks that require spatial thinking?

Many spatial tasks can be performed computationally enabling us to efficiently store, model, and analyze large sets of spatial data and solve complex spatiotemporal problems. In engineering, design, and the arts computer-aided design (CAD) and 3D modeling software are used to interactively, computationally model, analyze, and animate complex spatial forms. In scientific computing spatial patterns and processes can be mathematically modeled, simulated, and optimized. Geographic information systems, for example, can be used to computationally store, model, analyze, simulate, and represent geospatial patterns and processes. The open source project GRASS GIS for example supports 'geospatial data management and analysis, image processing, graphics and maps production, spatial modeling, and visualization' [GRASS Development Team 2016].

Computing mediates and transforms spatial thinking, expanding, but also constraining what is possible. While spatial computing can augment spatial thinking – distributing or offloading cognitive processes through digital computation – the logic of implementation, the limits of what is computationally possible, and the modes of input and output constrain how we reason. Furthermore, when it is difficult to interact with a computer, to input commands and parse the resulting output, one has to think harder and risks frustration and demotivation.

Unintuitive modes of human-computer interaction constrain thought and add cognitive and emotional costs. The paradigmatic modes for interacting with computers today – command line interfaces (CLI) and graphical user interfaces (GUI) – require physical input from devices like keyboards, mice, digitizing pens, and touch screens, but output data visually as text or graphics. Theoretically this disconnect between intention, action, and feedback should make interaction less intuitive [Dourish 2001; Ishii 2008]. Furthermore, it can be challenging to parse data that is only presented visually. Spatial data – especially 3D spatial data – presented graphically can require sophisticated spatial reasoning skills such as mental rotation [Shepard and Metzler 1971], spatial visualization, and spatial perception [Linn and Petersen 1985] to parse and understand, much less manipulate.

1.2. Tangible interaction

Tangible interfaces – interfaces that couple physical and digital data [Dourish 2001] – are designed to physically manifest digital data so that we can cognitively grasp and absorb it, so that we can think with it rather than about it [Kirsh 2013]. Ishii and Ullmer envisioned that tangible interfaces would 'take advantage of natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and information' [Ishii and Ullmer 1997]. With a tangible interface both input and output are physical. Data can be felt as well as seen; data can be directly, physically manipulated, leveraging highly developed motor skills. Thus intention, action, and feedback should be seamlessly connected enabling automatic, subconscious, and intuitive interaction.

Tangible interfaces let users interact with computers while (functionally) thinking with their bodies. By thinking with their bodies, by embodying cognition users may be able to reduce their cognitive loads by offloading cognitive tasks like spatial perception and manipulation onto the body and physically simulating processes. In embodied cognition higher cognitive processes are grounded in, built upon, and mediated by bodily experiences such kinaesthetic perception and action [Hardy-Vallée and Payette 2008]. When people use tools they temporarily, contingently incorporate them into their body schema, feeling the perimeter, weight, and balance of the tool, sensing resistance when the tool touches something, as if the tool was an extension of the body [**?**]. Because tools can be cognitively gripped and absorbed in ones body schema, they mediate embodied cognition – affording new bodily experience and action and thus extending ones capacity for thought. Tangible interfaces are designed to make computation tangible so that it can be cognitively gripped and absorbed, so that computation can be understood with the body.

It can be challenging and cognitively taxing to visually perceive and parse space, to for example visually judge distances and imagine volumetric form. Distance and physical properties like size, shape, volume, weight, hardness, and texture, however, can be automatically and subconsciously assessed kinaesthetically with the body [Jeannerod 1997]. By affording physical feedback tangible interfaces should, therefore, reduce the cognitive load needed to judge spatial distances, relationships, patterns, and forms.

Furthermore, some cognitive processes can be physically simulated, offloading the cognitive work onto the body [Kirsh 2013]. Dancers for example use marking – a simplified, abstraction of a dance phrase – to learn and practice elements or apsects of the phrase.

Marking is

a model a sketch-through-action

[Kirsh 2013]

...

Architects massing models Office of Metropolitan Architecture foam massing models [**?**] or Frank Gehry's creative process of thinking through the movement of gestural drawing and exploratory form finding with massing models [**?**; **?**]

...

When tangible interactions are designed to be analogous to everyday, physical tasks like unscrewing a bottle top [Kirsh 2013], picking up and placing objects, or sculpting sand... users may already understand what to do. Such interaction should be highly intuitive, drawing on existing motor schema and cultural knowledge.

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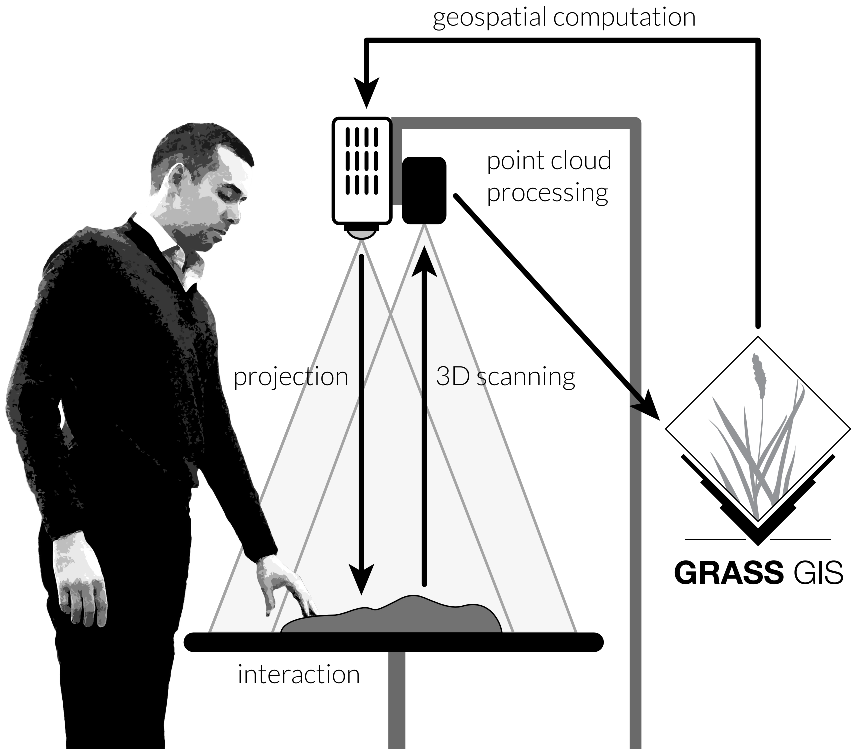

Fig. 1. Caption.

2. METHODOLOGY

2.1. Tangible Landscape

Concept. A tangible user interface powered by open source GIS. Coupling a digital and physical model of a landscape so that you can intuitively feel and shape it with your hands. Near-real time interaction.

Evolution. An evolution of Illuminating Clay and the Tangible Geospatial Modeling System.

Design. Tangible Landscape couples a digital and a physical model through a continuous cycle of 3D scanning, geospatial modeling, and projection. Intuitive scientific modeling with Tangible Landscape. Tangible Landscape is designed to make scientific data, models, and simulations exploratory, engaging, and fun.

Figure 1 . . .

Modes of interaction.

Applications.

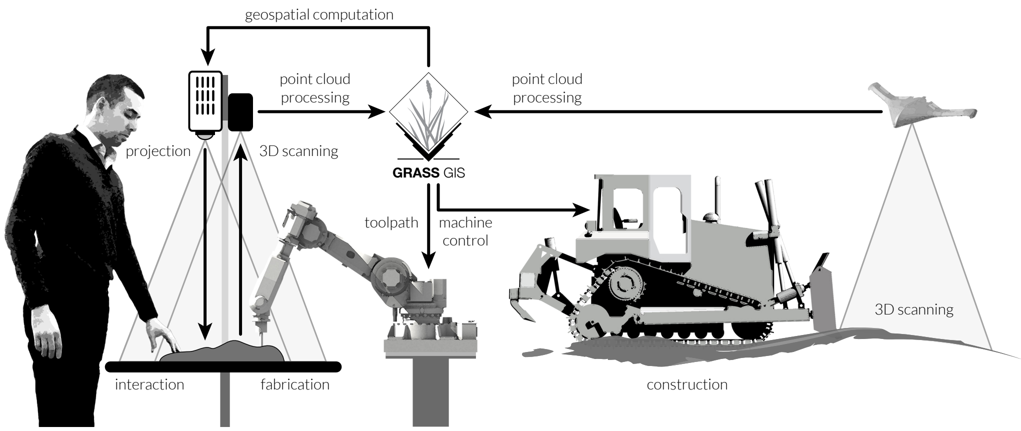

Fig. 2. Tangible Landscape with robotic fabrication, robotic construction, and real-time field data

2.2. Coupling experiment

2.3. Analytics experiment

2.4. Case studies

Coffee & Viz. Scientific gaming: Structured problem solving with rules, challenging objectives, and scoring

3. RESULTS

4. DISCUSSION

5. FUTURE WORK

Figure 2 . . .

6. CONCLUSION

APPENDIX

In this appendix . . .

ELECTRONIC APPENDIX

The electronic appendix for this article can be accessed in the ACM Digital Library.

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Online Appendix to: Embodied Spatial Cognition in Tangible Computing

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