Tangible Landscape: A Hands-on Method for Teaching Terrain Analysis

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Tangible Landscape: A Hands-on Method for Teaching Terrain Analysis

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Figure 1: (a) Participants interacting with Tangible Landscape during the pilot study to learn about topographical properties relevant to (b) hydrology; (c) geomorphology; and (d & e) land surface grading.

ABSTRACT
This paper presents novel and effective methods for teaching about topography–or shape of terrain–and assessing 3-dimensional spatial learning using tangibles. We used Tangible Landscape–a tangible interface for geospatial modeling–to teach multiple hands-on tangible lessons on the concepts of grading (i.e., earthwork), geomorphology, and hydrology. We examined students' ratings of the system's usability and user experience and tested students' acquisition and transfer of knowledge. Our results suggest the physicality of the objects enabled the participants to effectively interact with the system and each other, positively impacting ratings of usability and task-specific knowledge building. These findings can potentially advance the design and implementation of tangible teaching methods for the topics of geography, design, architecture, and engineering.

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INTRODUCTION

Tangible user interfaces (TUIs) have the potential to fundamentally transform spatial education by enabling embodied interaction with spatial computations. Spatial computations–such as digital mapping, modeling, analysis, and simulation–can help people learn about spatial patterns and processes–such as understanding the shape of the earth's surface or the pattern of water flow. Graphical user interfaces (GUIs), the paradigmatic mode of interacting with computers, constrain how users interact, perceive, think about, and thus learn about space with input limited to pointing devices and keyboards and feedback to graphics. With TUIs, users can sense, move, and transform digital data kinaesthetically with their bodies, enabling embodied cognition, i.e., thinking grounded in bodily presence and experience of 3-dimensional (3D) space [12]. Because our understanding of space is grounded in our bodies, TUIs should theoretically enable more rapid, intuitive learning about space through embodiment. TUIs like the Augmented

Reality Sandbox are being rapidly adopted for spatial education at all levels from primary schools to universities [13]. Given the recent accelerated development and adoption of TUIs for spatial modeling, there is a scarcity seen in the development of appropriate methods–and related examination of these methods–to empirically assess spatial learning using tangibles. Therefore, it is increasingly important to study how to effectively teach about space and assess spatial learning using tangibles.

The focus of this research was to develop and assess a novel method for teaching about topography and hydrology using Tangible Landscape, a tangible interface for geospatial modeling. To do so, multiple hands-on tangible teaching lessons with the themes of waterflow, landforms, and earth moving (i.e., cut and fill) were developed and implemented. These lessons were in the format of weekly workshops, embedded in a graduate-level grading course. The effectiveness and usability of Tangible Landscape as a teaching tool was then assessed by examining students' ratings of the system's usability and user experience, and students' acquisition of spatial skills (e.g., reading and interpreting topography). We report the experiment procedure, present the results, and finally discuss them in terms of knowledge building, user experience, and implications for education. This research is unique as although previous studies have shown how students' 3D spatial performance can be enhanced with tangibles [6, 26, 42], there remains a paucity of research investigating how to design, implement, and assess the effectiveness of tangible teaching methods–and usability of the associated tangible interface–for geospatial learning.

BACKGROUND

Embodied Interaction

Theories of embodied cognition assert that the mind is displaced throughout the body [12]. Higher order cognition relies on sensorimotor processes, linking perception and action together. This linkage of perceptual processes and action allows cognition to be physically simulated and offloaded with body movement. Tools needed to solve spatial problems can be cognitively grasped, understood, and then simulated into one's body schema [4]. As such, feeling, action, and thought are functionally integral to cognition. With this in mind, human-computer interaction (HCI) researchers propose there is an inherent divide between natural thought processes and the virtual confinement of traditional computer interaction–2D screens with limited modes of interaction (i.e., mouse and keyboard) [8]. Specifically, researchers suggest there is a theoretical disconnect between the visual modality of GUIs and the natural, physical environment in which we live [8]. In fact, GUIs are inflexible in use, and visually inadequate regarding users' perception and processing of critical information [8]. In the context of geospatial analytics and Geographic Information Systems (GIS), users must manipulate real-world geospatial data sets with physically constraining virtual toolkits, limiting the ways they can think about the geospatial data being represented. This makes it difficult for the user to perform spatial tasks, which can potentially lead to increased levels of cognitive load, and raises the likelihood that the user will become frustrated, lose motivation, reject the system being used, and ultimately drop the task entirely or modify the interaction to his/her own requirements [5].

Tangible User Interfaces

There is potential to bridge this theoretical divide seen with GUIs by changing the mode of interaction to a more intuitive and natural modality–Tangible User Interfaces (TUIs). TUIs provide interactive, tangible, and physical spatial data, allowing users to cognitively grasp and kinesthetically manipulate complex 3D data and therefore, support more effective and natural learning [32, 38, 43].

Several Tangible User Interfaces (TUIs) which enable geospatial modeling already exist. Specifically, there are actuated pin tables (e.g., XenoVision Mark III Dynamic Sand Table, Northrop Grumman Terrain Table, Relief, Recompose, Tangible CityScape, inFORM), augmented architectural models (e.g., Urp, Collaborative Design Platform), augmented clay (e.g., Illuminating Clay, Tangible Geospatial Modeling System), and augmented sandboxes (e.g., Sandscape, Tangible Landscape, Inner Garden, etc.) (see [6] for an overview of existing TUIs). Actuated pin tables, such as Relief [14], can be categorized into three distinct categories: transformable tangible interfaces [9], dynamic shape displays [22], or shape changing interfaces [25]. While interacting with these systems, users can feel the tangible model for passive feedback, observe computational transformations for active feedback, and see projected, graphical feedback. Projection-augmented tangible interfaces (e.g., augmented architectural models, augmented clay, augmented sandboxes) are physical models, augmented with visually projected analytics. They use object recognition, computation, and projection to provide users with an interface that couples a physical and digital model together to create a deformable, continuous tangible interface that users can physically modify to meet any current task goals and requirements [20]. However, the majority of these systems lack advanced geospatial modeling capabilities (i.e., analyses) and therefore cannot flexibly nor appropriately accommodate various teaching applications for spatial education (e.g., math, design, geography).

Tangibles in Education

Spatial education researchers have shown that when curricula are constructed to help students improve spatial ability and skills, it directly results in improved success in their spatially-focused courses (e.g., algebra, geometry, geography, design, architecture, engineering) [7, 33, 41]. However, students at times find difficulty with visualizing spatial relations such as object shapes, relative locations, and how these change over time [15]. This difficulty has been described as one of the main hurdles currently hindering students' success in geoscience and other spatially-focused classrooms [23, 27, 28, 39]. One solution involves using tangibles in the classroom, as they have previously been shown to enhance spatial ability by affording embodied interaction and improving perception through visual and haptic feedback [42]. Although there are indications that incorporating TUIs in school curricula is useful, the evidence is sparse [6, 26]. As such, there is a need to combine the use of TUIs to deliver tangible teaching methods developed from core curriculum requirements to help students improve their spatial skills and learn more naturally and effectively. We propose that

TUIs will allow students with little to no computer experience to interactively explore, model, visualize, and think about complex, spatial scientific problems–infused with geoscience curricula (e.g., Terrain Analysis for Landscape Architecture students) and representative of real-world geographic issues–directly resulting in positive learning experiences and topic-specific knowledge building.

Typical Teaching Methods for Terrain Analysis

Typical methods for teaching terrain analysis include in-situ surveying, drawing contour maps, and building physical models. While surveying teaches students how topographic data is collected, drawing exercises involve interpolating contours from spot elevations and designing contour plans for new topographic features. Physical modeling exercises include building clay models and contour models of existing or designed topography (see [21, 34, 40] for examples of commonly used textbooks). Of these teaching methods however, only field work and physical modeling exercises directly teach students how to translate between 2D and 3D space. Systems such as Tangible Landscape can overcome traditional teaching methods' shortcomings by providing students' with a physical and interactive manifestation of 2D map projections, allowing students to associate 2D field, map, and GIS data simultaneously with complex, 3D landscape structures and therefore reduce the cognitive burden of computing what is logically implied by 2D spatial information [1, 12]. Furthermore, tangible teaching methods can cover complex geomorphological topics such as process-form interaction by dynamically linking 3D topographic form with hydrological and erosive processes.

TANGIBLE LANDSCAPE

Concept

Tangible Landscape is a TUI designed to support natural, embodied interaction with 3D spatial data. Tangible Landscape couples a physical and digital model of a landscape through a continuous cycle of 3D scanning, geospatial modeling, and projection so that users can intuitively interact with the modeled landscape and the corresponding simulated physical processes in real-time [20, 36, 35]. During this more hands-on approach to interacting with 3D spatial data, students become active participants in the scientific inquiry process as the system allows them to iteratively observe natural phenomena, generate inferences, form hypotheses and test them, and draw conclusions. Powered by an open-source GIS software called GRASS GIS [17], which contains over 300 simulation modules developed and maintained by the scientific community, Tangible Landscape can be flexibly programmed to accommodate simple to complex geospatial applications and simulations and thus, provides a much broader range of teaching opportunities than preceding geospatial TUIs. Examples of these applications include landform analysis, elevation difference analysis, erosion modeling, firespread, plant disease modeling and many others [20].

Design

The Tangible Landscape system integrates four main computational components: (1) 3D scanning (of physical model); (2) point cloud processing; (3) geospatial computation; and (4) projection. As users change the physical model, the model is 3D scanned as a point cloud, georeferenced, imported into GRASS GIS, and either binned or interpolated as a digital elevation model. The digital elevation model is used to compute geospatial analyses, models, and simulations, which are then projected back onto the physical model, all in real-time.

Tangible Landscape as a Teaching Tool

Tangible Landscape has the potential to transform existing teaching methods within the hard sciences (e.g., biology chemistry, physics, geography), social sciences (e.g., sociology, human geology), and mathematics by combining computer-based design and embodiment. With Tangible Landscape, users can physically interact with digital models and simulations by sculpting, placing objects, or sketching (Figure 2). These various modes of interaction enable students to immediately see how they are changing terrain properties like contours, hillslope steepness, or water flow. By kinesthetically feeling and manipulating the shape of the topography, while seeing projected geospatial simulations or analyses, students can intuitively learn about 3D topographic form, topographic representations (elevation colors, contour lines), real-world manifestations of topography (e.g., landforms), and how topography controls physical processes like the flow of water.

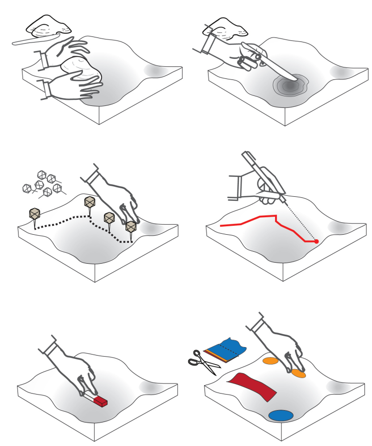

Figure 2: Modes of interaction with Tangible Landscape (from left to right): Sculpting topography with hands; Sculpting with tools; Placing markers to establish way-points; Drawing walking routes; Establishing viewpoints; Patch placement for planting vegetation.

PILOT STUDY

Grading, (i.e., earthwork), is an important part of the practice of Landscape Architecture. It is part of the core curriculum in accredited professional Landscape Architecture degrees and is tested in the Landscape Architect Registration Examination. There are analog and digital methods for teaching grading including hand drawing, model-making by hand, computer-aided design, and computer-aided manufacturing. Analog methods afford embodied cognition and thus promote intuitive spatial perception and learning [4]. Digital methods afford easy replicability and quantitative modeling and analysis. In this study, we aimed to test the effectiveness of a hands-on (i.e., analog) method for teaching concepts–which require 3D spatial thinking–of grading, geomorphology, and hydrology using

Figure 3: Progression of a tangible lesson (from left to right): (a) Instructor giving an overview of the lesson content and tasks; (b) Presentation of specific task objectives; (c) A pair of students performing a tangible task while being monitored by the researcher; and (d) Example of a tangible task (landforms).

Tangible Landscape. The study consisted of three, one-week sessions that were comprised of tangible lessons designed to teach the fundamentals of grading, geomorphology, and hydrology using Tangible Landscape. The lessons were designed and framed as structured tasks to encourage learning through direct and guided instruction [3]. Participants were not graded on their performance. The first lesson focused on teaching water flow with a flowpath sub-task, a channeling sub-task, and a ponding sub-task. The second lesson focused on teaching landforms which required participants to build and identify landforms of increasing complexity. The third and final lesson was centered around teaching cut and fill (i.e., earth moving), where participants attempted to change landscapes based on provided contours, also of increasing complexity. We assessed the effectiveness of Tangible Landscape as a teaching tool through a user experience survey and pre-and posttests (e.g., 18-item map assessment, lesson-specific pen and paper assessments).

METHODS

Participants

16 graduate students from a Landform, Grading, and Site Systems course[1] in the Department of Landscape Architecture at North Carolina State University participated in this study. The majority (N = 10) of participants' ages ranged from 18-24 years old, while the remaining participants' ages ranged from 25-34 (N = 5), and 35-44 years old (N = 1). The participants voluntarily took part in the study as part of the college course during class time. Participants were divided into pairs based on their preference and worked with the same collaborator on the tangible lessons for the entirety of the 3-week study. Each participant provided informed consent for participating in the study and to be recorded by camera and video.

Study Environment and Apparatus

The study environment included a conference room (Figure 3a) and adjacent workshop room (Figure 3b). In the workshop room, there were three Tangible Landscape systems set up 5m away from each other. Each Tangible Landscape setup included a computer, projector, 3D sensor, an armature to hold the projector and sensor, and a physical model of a landscape. The computer was a System 76 Oryx Laptop, operating on Linux with GRASS GIS–an open source software for geospatial modeling and analysis–with Tangible Landscape plugin[2], r.in.kinect add-on[3], and their compiled dependencies. The physical landscape models were malleable models made of a soft, deformable polymer enriched sand. These models were precisely casted with digitally fabricated molds based on local regions (e.g., Asheville, North Carolina, USA). The 35x35cm physical models of the landscapes (size selected to reduce system processing time) were placed on a table with a mounted Kinect sensor–an efficient and inexpensive 3D scanner containing modules which allow for seamless connection to GRASS GIS–attached to a C-stand. The height of the C-stand was calibrated so that the Kinect was 50-100cm above the model (see Figure 4). Before any tasks were run, the system was calibrated by removing the physical landscape model, clearing the table, and then running Tangible Landscape's automatic calibration function to account for the relative rotation of the scanner and the table.

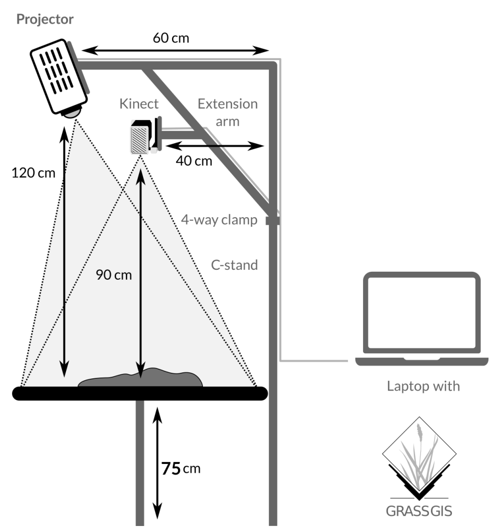

Figure 4: Tangible Landscape system setup.

Study Procedure

The tangible sessions all followed the same format in that they each involved four steps: (1) a paper-based pretest, (2) a brief introduction explaining the aim of the research study and lesson content, (3) tangible lessons, and (4) a paper-based posttest. At the beginning of each session (i.e., each week), participants were greeted by the researchers, and then asked to complete the pretests. Upon completion of the pretest (approximately

[1] https://osf.io/7urtd/
[2] github.com/tangible-landscape/grass-tangible-landscape
[3] github.com/tangible-landscape/r.in.kinect

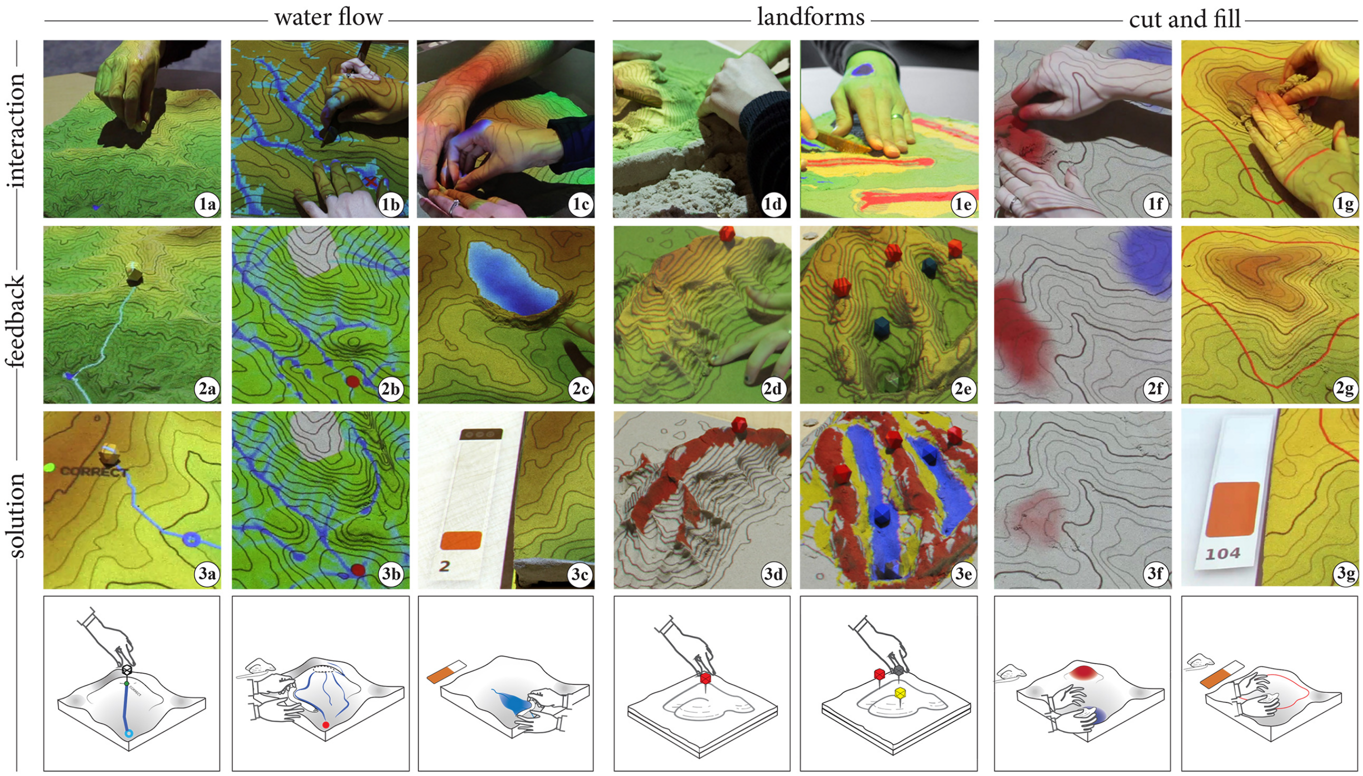

Figure 5: Interaction, feedback, example solutions for tangible teaching lessons, and illustrations of prototypical task interactions.

30min), participants were given a brief slide presentation regarding the lesson content and overall goals of the study. The first session's format was slightly different as it consisted of a more comprehensive pretest (topographic map assessment (TMA) [19]), and additional presentation slides introducing Tangible Landscape, its features, and various applications. After the presentation, and before beginning the tangible tasks, three student pairs were guided to the workshop room and were presented with a series of slides showcasing a real world problem description, specific task objectives, scoring and time details, and a step-by-step instructional video showing how to perform the tasks. For example, the real-world scenario presented for the landforms task was:

> *The Geoscience Department of a university has asked you to design a land art installation for their campus. For educational purposes the installation should represent a set of basic landforms. The faculty have suggested several different sets of landforms and would like to see a design for each. The basic landforms are peaks, ridges, shoulders, spurs, slopes, pits, valleys, footslopes, and hollows*.

Following the video, the projection screen transitioned to specific task instructions, which were displayed throughout the entirety of each task. Tasks were performed on specific stations, each operated by a researcher (Figure 3c and 3d). Immediately after the task was completed, participants were administered a posttest (modified version of the pretest). The procedure repeated for another two rounds with three and two student pairs, respectively. Two weeks after the last session, researchers went to the class and administered the TMA posttest (modified version of pretest) and the user experience survey [24]. Please see Figure 3 for an example of the landforms session progression.

Tangible Lessons

The study included three tasks focused on understanding (a) water flow, (b) landforms, and (c) changing landscape surfaces by cut and fill (i.e., earth moving).

Water Flow

The water flow lesson included three tasks: flowpath, channeling, and ponding. For the flowpath task, participants were asked to find the highest source point from which water will flow into the target point in the landscape (Figure 5-1a). At the start of the task, the first target point was illuminated on the model. Participants then marked the location of their source point location by inserting a wooden pin into the model. The flow path was computed using module *r.drain* [37] and then projected on the model (Figure 5-2a). This enabled them to explore various source point locations and verify whether the flowpath reached the target point or not. Once participants were satisfied with the projected solution (Figure 5-3a), they pressed a button to observe the correct solution and then proceeded to the next point. This task included a total of 7 points, each containing increasingly difficult solutions. However, if participants took longer than 10 minutes, then the sub-task would end.

The channeling task required participants to modify the terrain surface–while making minimal changes to the landscapes–to make water flow from the given source point to the given target point. Participants were allowed to use their hands or wooden sculpting knife to shape the topography by placing and shaping the provided sand (Figure 5-1b). Using overland flow simulation implemented in module *r.sim.water* [16], [37] the projected flow paths (Figure 5-2b) were continuously updated based on participants' changes to the topography to ultimately direct the water to the solution point (Figure 5-3b). The total task time was 10 minutes.

For the last task, ponding, participants were given a limited amount of sand to build a damn on a stream to impound the maximum volume of water. They used their hands or a sculpting knife to make dams or depressions in the landscape (Figure 5-1c). The ponding was simulated using the module *r.fill.dir* [37] and projected on the model (Figure 5-2c). The surface water area and impounded water volume were projected as a changing bar chart next to the model (Figure 5-3c). It is important to note that for all of the tasks, elevation color and contours were projected onto the sand model.

Landforms

The landforms lesson consisted of three sub-tasks: simple, compound, and complex landforms. Each sub-task required participants to create and identify given landforms; each subtask was completed in three rounds of increasing difficulty. For the simple landforms, participants built and identified one depression during round one, one ridge for round two, and one valley during round three. For round one of the compound landforms task, participants were required to properly build and identify two ridges and one valley, one peak, one valley, and one depression for the second round, and two valleys and one depression for the third round. During the final sub-task, complex landforms, three ridges and three valleys were required for round one, for round two, three peaks, one depression, and two ridges, and for round three, one footslope and one spur. Each sub-task lasted 15min (5min per round). After they created the landforms (using their hands or a sculpting knife) (Figure 5-1d & e), the module *r.geomorphon* [10, 37] was run to analyze the topography and project detailed feedback (Figure 5-2d & e) on the types of landforms created (Figure 5-3d & e).

Cut and Fill

The cut and fill, i.e., earth moving, lesson consisted of two tasks: basic modeling using elevation difference feedback and advanced modeling using elevation contours with numerical feedback. For the basic modeling task, participants modified a given landscape using cut and fill projection (Figure 5-1f). At the start of the sub-task, the elevation difference of the existing landscape and the expected landscape were computed by subtracting the scan from the digital elevation model of the expected landscape and projected as red and blue colors (Figure 5-2f). Specifically, blue indicated the areas where sand should be added (fill) and red indicated the areas where sand should be removed (cut) either by hand or with a sculpting knife. The color intensity indicated the magnitude of difference and turned white when the target elevation was reached (Figure 5-3f). In addition to colors, the contour map was continuously updated and projected. This task lasted a total of 10min.

During the advanced modeling task, participants were required to build a landscape using contour lines (Figure 5-1g). At the start of the task, the areas on the landscape in which cut and fill should be performed were highlighted, as well as a contour map of the expected elevation (Figure 5-2g). The only feedback provided included how much total elevation difference was between the scanned model and the expected landscape, presented in numeric format (Figure 5-3g).

Materials and Scoring

Topographic Map Assessment

To assess students' acquisition and transfer of spatial skills (related to understanding how elevation is encoded on topographic maps and how 3D terrain shape is represented on maps), modified versions (i.e., different map terrains with same question text) of the topographic map assessment (TMA)[4] [19] were administered in the first session and two weeks after the last session. When taking the TMA, students must access multiple levels of geographic understanding, as they are required to use topographic maps in a variety of ways. For example, the TMA contains three types of topographic map test items: (1) elevation items–questions which require an understanding of how elevation is represented through contour lines; (2) shape items–comprehension of 3D shapes within the represented terrain; and (3) shape and elevation items–questions that contain both the aforementioned constructs. The assessment consisted of 17 questions with 17 possible points. Correct answers were given a score of 1, partially correct answers were scored as 0.5, and incorrect answers received a score of 0. An answer was scored as partially correct if it was a two-part question, and the participant correctly answered only one of the parts. For example, for the question that asked participants "Imagine there is a stream that connects the circle and the square. In which direction would the water flow? Please draw the path the stream would take." the participant would receive a partially correct response (0.5) if they correctly sketched the water path based on the given map's contour lines but could not identify the correct direction the water would flow (e.g., circle to square). A primary and secondary coder scored all the assessment responses. Any disagreements between the researchers were settled through discussion and the inter-rater reliability was calculated to be 95%.

Tangible Lesson Assessments

We developed two additional pen and paper assessments to measure student's knowledge specific to tangible lesson content (landforms[5], cut and fill[6]) to be administered before and after the Tangible Landscape tasks. Since the TMA already contained questions that addressed constructs of topography and corresponding flow of water, we only administered pre- and posttests for the landforms and cut and fill lessons. The landforms assessment included a contour map of a mountainous area (region in Asheville , North Carolina) showing 10 red annotated rectangular boundaries. Students were asked to identify and write the landform type (out of five types total) inside the boundary. Of those 10 boundaries, eight were related

[4] https://osf.io/znxd8/
[5] https://osf.io/hscx6/
[6] https://osf.io/pxt36/

to simple landforms (peak, ridge, valley, channel) and two were complex landforms (spur, hollow). A modified version of this assessment (i.e., contained a different contour map from the pretest) was administered when the task was completed. The cut and fill, i.e., earth moving, assessment included two problems–a simple and complex–corresponding to the tasks completed with Tangible Landscape. The first problem depicted a contour map of a landscape before the cut (excavation) and fill (embankment) operations, as well as a 3D bird-view of that landscape after cut and fill. Students were required to highlight areas in the contour map that had undergone cut and fill operations. The second problem included a contour map, two 3D bird-eye views, and three section profiles. The contour map depicted a landscape with two demarcated blank regions. The 3D views and profiles provided detailed information about the expected topography inside the demarcated region. Using this information, students were required to complete the contour lines inside the blank region. The correct answers for both the landforms and cut and fill assessments were precomputed in GRASS GIS, and then used by researchers to quantitatively score participants' responses. As with the TMA, a primary and secondary coder again scored participants' responses on both the landforms and cut and fill assessments. Inter-rater reliability was calculated to be 92%.

User Experience Survey

We used an adapted version[7] of Ras and colleague's [24] user experience survey specifically designed and validated to evaluate usability and user experience of geospatial TUIs. The survey alleviates tension recently seen in user experience research, as emerging and innovative technologies (i.e., TUIs) do not match with more traditionally constructed assessments (i.e., paper-based). Specifically, the survey examines how users perceive and interact with a TUI, and how they collaborate to solve a problem [24]. The primary constructs the user experience survey assessed were performance expectancy, pragmatic quality of both the physical (wooden carving tools, physical landscape model) and visual objects (projection, digital feedback), effort expectancy, and user experience. Performance expectancy refers to the degree to which a user thinks using the system in question will assist them in attaining higher levels of performance during a specific task. Effort expectancy is known as a system's perceived ease of use, while user experience focuses on overall satisfaction, comfort, and perceptions of the system's effectiveness [2]. Each item within the constructs used a 7-point Likert scale with a neutral value of 4.

RESULTS

We evaluated participants' acquisition and transfer of spatial skills (i.e., knowledge building) by computing and examining participants' mean scores on all paper-based assessments taken before and after each exercise (landforms, cut and fill) as well as the TMA taken before and after the 3-week study. For analyses examining potential knowledge building, we employed the paired samples t-test as it measures the same participants at multiple time points (before and after interaction) allowing the participants to act as their own control, resulting in increased power and a higher chance of detecting a significant difference.

[7] https://osf.io/atjcg/

Knowledge Building

Landforms Assessment

As seen in Figure 6, participants' scores on the landforms pretest ranged from 16.67% to 100.00% (*M* = 56.77, *SD* = 23.61) while posttest scores ranged from 8.33% to 91.67% (*M* = 55.21, *SD* = 22.54). A paired t-test was conducted on participants' mean landform response accuracy to determine if there was a significant difference between administration time (Pre –> Post). Results revealed no significant response accuracy differences for landform assessment time (t(-0.22), p = .831) (Figure 7).

Cut and Fill Assessment

Participants' cut and fill, i.e., earth moving, pretest scores ranged from 20.00% to 78.50% (*M* = 53.25, *SD* = 19.27). Posttest scores ranged from 25.00% to 80.00% (*M* = 59.97, *SD* = 16.14) (Figure 6). A paired t-test for cut and fill revealed a significant increase in participants' mean response accuracy between pre- and posttest (t(2.73), p = .016). Specifically, after having completed the cut and fill tangible lesson, participants performed significantly higher on the cut and fill assessment (post (*M* = 59.97, *SD* = 16.14)) when compared to performance on the assessment before the lesson (pre (*M* = 53.25, *SD* = 19.27)) (Figure 7).

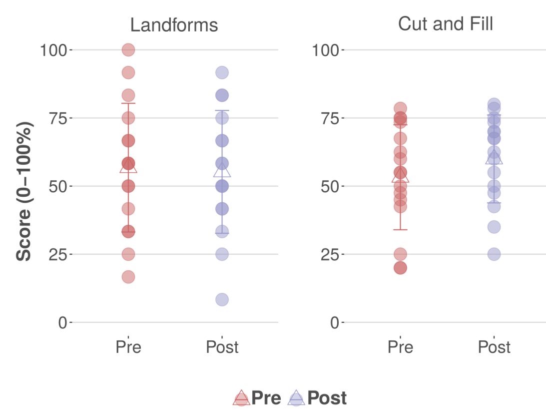

Figure 6: Distribution of participants' individual scores on the landforms and cut and fill assessments.

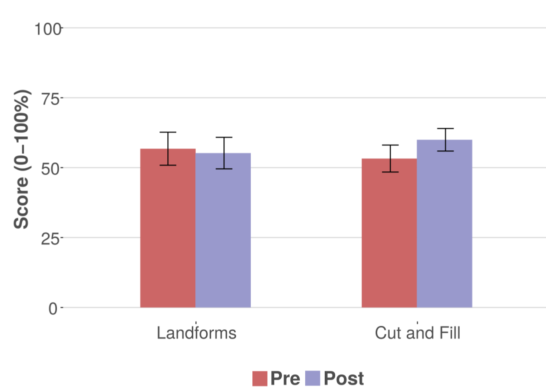

Figure 7: Participants' mean scores on the landforms and cut and fill assessments. Error bars represent one standard error of the mean (i.e., 95% confidence intervals.)

Topographic Map Assessment

Descriptive statistics for overall TMA responses showed that both on the pretest (*M* = 76.10, *SD* = 11.90) and posttest (*M* = 73.93, *SD* = 15.57), the majority of participants (*N* = 12) scored above 70% (Figure 8). A paired t-test was conducted to assess whether there were significant differences in participants' mean TMA response accuracy between TMA administration time (Pre –> Post). Results revealed no significant differences (*t*(-0.66), *p* = .521) (Figure 9). Paired t-tests were then conducted by TMA question type (i.e., elevation, shape, and shape and elevation items) to assess significant differences in response accuracy across multiple levels of geographic understanding. Results showed no significant differences for shape (*t*(1.10), *p* = .287), elevation (*t*(-0.11), *p* = .918), or shape and elevation (*t*(2.01), *p* = .08) (Figure 9).

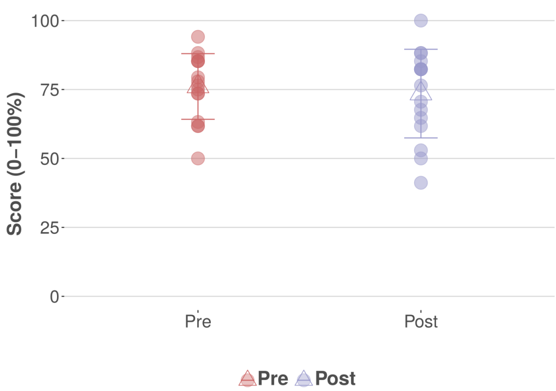

Figure 8: Distribution of participants' individual scores on the TMA.

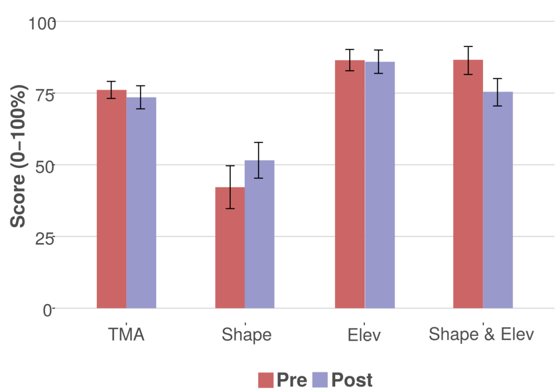

Figure 9: Participants' mean scores on the TMA and by question type. Error bars represent one standard error of the mean (i.e., 95% confidence intervals.)

Usability and User Experience

Table 1 shows the descriptive results for each scale. By looking at the descriptive statistics of the constructs, we observe that they all pass the neutral value of 4, meaning users rated the system positively. On average, the users ranked the effort expectancy of the system the lowest (*M* = 5.30, *SD* = 0.59), while performance expectancy was rated the highest (*M* = 6.51, *SD* = 0.59). From the perspective of performance expectancy, the aspects of Tangible Landscape's environment that were found to be the most advantageous were ability to explore various solutions for the given problems (e.g., water flow, landforms, cut and fill) (*M* = 6.63, *SD* = 0.62). Users also reported that the physical objects (e.g., wooden markers and sculpting knife) allowed them to change parameters (e.g., location of solution points, adding or removing sand) very quickly (*M* = 6.63, *SD* = 0.62) and that the projected visual feedback helped them better understand the effects of changing those parameters (*M* = 6.38, *SD* = 0.84). From a user experience point of view, participants highly rated the system as being both 'captivating' (*M* = 6.50, *SD* = 0.73) and 'innovative' (*M* = 6.31, *SD* = 0.87). Lastly, the physical objects (e.g., wooden markers, sand, sculpting knife) and the visual objects (e.g., contours, elevation color) were highly rated as practical in their quality (physical objects: *M* = 6.25, *SD* = 0.78; visual objects: *M* = 6.13, *SD* = 1.09).

Construct	*Mean*	*Std. Dev.*
Performance Expectancy	6.51	0.59
Pragmatic Quality (Physical)	5.64	0.99
Pragmatic Quality (Visual)	5.81	0.94
Effort Expectancy	5.30	0.59
User Experience	5.66	0.50

Table 1: Descriptive statistics of the user experience survey (N = 16).

DISCUSSION

This paper focused on developing and assessing new ways to teach about topographical properties and assess 3D spatial learning using tangibles. We specifically assessed the usability and effectiveness of using a Tangible User Interface (TUI)–Tangible Landscape–to teach tangible lessons relevant to land surface grading, geomorphology, and hydrology. Our results suggest that overall, the physicality of the objects enabled the participants to effectively interact with the system and with each other and, hence, positively impacted their overall experience with the system. Additionally, our findings provide preliminary evidence that Tangible Landscape supports both improved user experience as well as marginal, task-specific knowledge building. These results have several implications for the design and implementation of tangible teaching methods for learning about Landscape Architecture and potentially other topics as well.

Knowledge Building

Our findings showed that participants performed significantly better on the cut and fill, i.e., earth moving, assessment after having completed the analogous task with Tangible Landscape. First, this can be explained by the ability to directly feel, grasp, and manipulate the various tangible materials (see Table 1 for ratings of the physical objects' pragmatic quality) [4, 8, 12]. However, this does not explain why only the cut and fill tangible lesson produced an increase in assessment scores (from pre- posttest). Potentially, the ability to interact with 3D space is more appropriate for learning about concepts of land surface grading–in comparison to other geospatial concepts–and therefore understanding how to best modify a given landscape to match the elevation model of an expected landscape. Second, because this task involved a logical progression in information perception (from simplistic color scheme to more advanced contour lines; e.g., basic modeling –> advanced modeling), it provides users with the connection between real and abstract representations [11]. Specifically, Tangible Landscape provides users with a real-time guide to help them better understand where to add or remove sand to match the target digital elevation model. This likely gives users a more concrete and simplified 3D physical representation of land surface change, leading to increased understanding of the concept as a whole, and then using this to better identify and comprehend more abstract, paper-based 2D representations when taking the assessment. This is important to note as traditionally there exists a vast difference in perception correspondence between real and abstract representations [11].

The majority of students in our study (75%) fell above the 3rd quantile in both the topographic map assessment (TMA) pre- and posttest. This raises the question of whether the TMA is useful in capturing the performance range of our expert landscape architecture students and relatedly, potential knowledge building from tangible lessons. While TMA is one of the few validated geospatial learning assessments and the only psychometrically valid assessment within the context of tangible interaction, it has only been tested for novice psychology students [19]. Moreover, the TMA solely focuses on using 2D contours to assess tangible-based knowledge building [18]. The TMA is restricted in this sense as it does not match the 3D modality of Tangible Landscape, and other tangibles alike. Although the TMA contained similar constructs as those presented with Tangible Landscape (e.g., water flow), matching participants' learning in tangibles to learning in a real-world situation (i.e., classroom with 2D paper-based assessments) does not guarantee that the cognitive activity linked with learning about topography will be similar across the simulated conditions. The construction of embedded assessments (i.e., administered within tangible systems) could prove to be the more useful way to evaluate students' ability to read and reason about topography. Measures of increased learning could, therefore, be taken into account according to specific perceptual states across learning domains with varying spatial thinking requirements (i.e., engineering vs geology).

User Experience

Results demonstrated that the objects' physicality enabled the participants to effectively interact with the system and with each other, positively impacting ratings of the system's usability and user experience. Specifically, Tangible Landscape lets users tinker, rapidly creating new iterations. It allows users to try, see and feel, and directly experience multiple variations of a given solution. Action is reversible with Tangible Landscape, and this encourages users to explore without risk of consequence [5]. This was seen with the high ratings of performance expectancy, specifically the reported benefits of being able to explore various solutions for the given problems (e.g., water flow, landforms, cut and fill) (see Results). This aspect allows users to engage in a natural learning process (i.e., learning by doing), allowing intuitive exploration and reflection on their solutions [29]. Moreover, results demonstrated how the visual feedback given (e.g., elevation color) enabled the participants to better understand the effects of changing topographic parameters (e.g., contours). Specifically, the system allows users to physically act upon tangible objects and immediately projects feedback to assist them in understanding how their actions (i.e., changes made to topographic features like slope or elevation) impact spatiotemporal processes like the flow of water over a landscape.

LIMITATIONS AND FUTURE DIRECTIONS

This study, as a pilot test, has several important limitations to distinguish. Most important is the limited methodological scope and low statistical power of the presented results as the current study was conducted with a small sample size and no control group (participants acted as their own control). This one-group pretest–posttest study design was selected as a preliminary evaluation technique to understand and describe Tangible Landscape in terms of its usability and effectiveness to teach spatial constructs. Results from this study are therefore limited as they can only inform researchers whether the tangible lessons enabled students to perform better on the administered tests. Specifically, any inferences made regarding potential knowledge building remain uncertain, relying more on multitheoretical perspectives on why the observed differences in test performance may have occurred (e.g., embodied nature of interaction, information perception). The chosen study design also raises concern regarding learning effects having influenced outcomes between the first and last set of tangible lessons. Considering the topics covered throughout the study sessions had little overlap (hydrology, geomorphology, grading), carry over (i.e., learning) effects influencing learning outcomes between lessons are unlikely. It is possible that students became more accustomed to the system and its associated affordances, leading to improved knowledge building during the last lesson (cut and fill). However, the likelihood of major practice effects occurring is low due to the system's ease of use and accessibility (see Results: Usability and User Experience) as well as the extensive interaction instructions provided in the first session and before each task (see Study Procedure).

With the above in mind, advisable adjustments for future studies include: (1) a more rigorous and complete empirical research design, constituted by between-group comparisons of different user interfaces and teaching methods; (2) manipulation of several important variables such as mode of interaction, afforded feedback, task structure, introduction of multiple participant groups, etc.; and (3) revision of the TMA for geospatial TUIs–specifically those which go beyond simply learning about contours (e.g., Tangible Landscape).

The most important question of what specifically caused the observed variance in knowledge building still needs to be answered. A promising approach may involve systematically assessing task performance such as spatiotemporal changes in physical models, number of attempts to solve a task problem (i.e., exploration), and overall scores [31]. Aside from systematic scoring, system log data can be used as valuable sources of information for quantifying tangible interaction, as shown in [30]. For instance, with Tangible Landscape it is possible to scan and analyze students' hand movement as sampled by the Kinect, as well as examine the changes in raster maps over time (i.e., time series analysis). Correlating this data with learning outcomes can provide valuable information on connections between task performance, tangible interaction, and spatial learning. Using more detailed and systematic scoring techniques will allow researchers to: (1) identify types of information (i.e., types of feedback) students need to effectively interact with tangible interfaces; (2) uncover and understand any learning issues (e.g., poor planning) that impede successful learning; and (3) understand when and in what context to use specific instructional methods (guided instruction vs free-play). As this paper primarily focused on presenting novel ways to use and assess a tangible interface for teaching, we suggest that an important area of future research will be to improve our understanding of which components of Tangible Landscape contribute to the higher than average user experience as well as the observed variance in knowledge building.

CONCLUSION

This research is unique in that it: (1) highlighted the potential of using a tangible interface–Tangible Landscape–to develop hands-on teaching tasks related to various geospatial, geographic, geological, planning, and landscape architecture topics; (2) demonstrated how using open-source GIS grants researchers the flexibility (i.e., ability to run various types of geospatial simulations) to develop specific tangible interface tasks (water flow, landforms, cut and fill); and (3) administered assessments–analogous to the tangible lessons and tasks–to measure student learning outcomes. Additionally, the observed variance in knowledge building speaks to the importance of systematically saving and recording interaction data (e.g., scanning of students' hands to quantify amount of interaction) to accurately process, score, and assess students' task performance. This, as well as using recorded log files to qualitatively explore interaction data will allow future researchers to uncover and understand any issues students experience when learning topics of geography, design, architecture, and engineering with tangible media. In sum, we argue that the main focus of future research should be on how geospatial learning outcomes are achieved, rather than only on what is achieved.

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