Visibility Perception and Dynamic Viewsheds for Topographic Maps and Models

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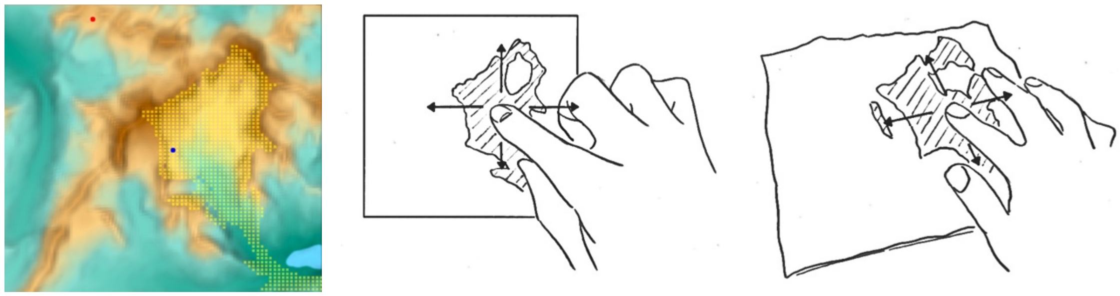

Figure 1: We explore the impact of dynamic viewsheds (left) which provide real-time interactive feedback about terrain visibility on both 2D touch-screens (middle) and 3D tangible terrain models (right).

ABSTRACT

We compare the effectiveness of 2D maps and 3D terrain models for visibility tasks and demonstrate how interactive *dynamic viewsheds* can improve performance for both types of terrain representations. In general, the two-dimensional nature of classic topographic maps limits their legibility and can make complex yet typical cartographic tasks like determining the visibility between locations difficult. Both 3D physical models and interactive techniques like dynamic viewsheds have the potential to improve viewers' understanding of topography, but their impact has not been deeply explored. We evaluate the effectiveness of 2D maps, 3D models, and interactive viewsheds for both simple and complex visibility tasks. Our results demonstrate the benefits of the dynamic viewshed technique and highlight opportunities for additional tactile interactions. Based on these findings we present guidelines for improving the design and usability of future topographic maps and models.

CCS CONCEPTS

• **Human-centered computing → User studies** • *Human-centered computing → Haptic devices*

KEYWORDS

Topographic maps, dynamic viewshed, geospatial visualization, terrain visualization, tangible user interfaces.

SUI '17, October 16–17, 2017, Brighton, United Kingdom

ACM ISBN 978-1-4503-5486-8/17/10…$15.00
https://doi.org/10.1145/3131277.3132178

ACM Reference format:

N. Li, W. Willett, E. Sharlin, M. Costa Sousa. 2017. SIG Proceedings Paper in Word Format. In *Proceedings of the 5th ACM Symposium on Spatial User Interaction, Brighton, UK, October 2017 (SUI'17)*, 9 pages.

https://doi.org/10.1145/3131277.3132178

1 INTRODUCTION AND MOTIVATION

Reading topographic maps is a notoriously challenging task, in part because the spatial topography these maps represent is inherently abstracted and distorted when projected into two dimensions [9][21]. As a result, common relative height judgement tasks like identifying peaks and valleys or assessing whether one location is visible from another can be difficult to perform, since they require the viewer to mentally reconstruct and reason about complex terrain geometry.

Using 3D terrain models in place of 2D topographic maps can mitigate some of these concerns, since elevation-related tasks become straightforward perceptual judgements. With a model viewers can directly examine lines of sight and compare the shape and size of topographic features without needing to decode elevations or mentally reconstruct the shape of the original terrain. However, because 3D models have traditionally been difficult to construct, move, and manipulate, they remain popular only in very limited circumstances such as in museums and visitor centers.

Recent research suggests that interaction techniques like interactive relief shearing [27], which animates terrain in order to provide additional depth cues, can improve terrain perception and elevation comparison for 2D maps. Meanwhile, digital fabrication technologies have made 3D terrain models increasingly easy to produce, and interactive systems like Illuminating Clay [19], Relief [13], TanGeoMS [24], etc. have demonstrated the potential for interactive and dynamic physical terrain models.

We revisit classic cartographic methods of legibility validation of topographic maps, and explore how interaction techniques can

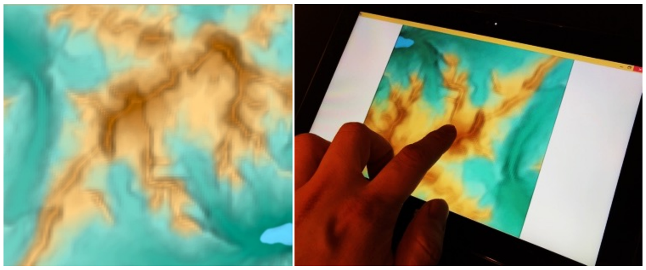

Figure 2: The 2D layer tinting map we used in the study (left) displayed on a Microsoft Surface (right); areas in brown have higher elevation and areas in green are lower.

enhance common tasks like comparing elevations and assessing lines of sight on both terrain maps and models. Specifically, we examine the impact of interactive *dynamic viewsheds*, which allow viewers to use touch to rapidly and interactively assess which locations are visible from various points on a map. We describe a study in which we asked participants to perform several types of visibility tasks, including assessing lines of sight and finding lowest-visible-points, using both 2D topographic maps and 3D physical topographic models, as well as maps and models that support dynamic viewsheds. Our results confirm that viewers make better relative height judgments with 3D models than with 2D maps, and that dynamic viewsheds improve performance for both representations. We also document viewers' responses to terrain maps and interactive dynamic viewsheds and describe common strategies that they used to solve visibility tasks. Based on these findings, we provide 3 guidelines to help guide the use of these technologies.

2 RELATED WORK

Over the past several decades, efforts to improve terrain perception have increasingly emphasized the use of stereoscopic displays, holography, 3D physical models, and other "True-3D" geo-visualization techniques as alternatives to traditional 2D cartographic representations [8]. In general, the push towards these technologies has been driven by the conventional wisdom that 3D representations can provide better spatial awareness of terrain than 2D maps. Because these techniques use 3D representations to display 3D terrain data, researchers have typically assumed that they will be easier for viewers to learn and will reduce cognitive load during map-related tasks [3].

Driven by the availability of digital scanning, projection, and fabrication technologies, tangible terrain models are now seen as a useful tool for a variety of GIS applications [16]. Digitally-augmented models and 2.5D shape displays, such as the MIT media lab's Illuminating Clay [19], Relief [13], and SandScape [11], and Nokia's experimental HERE installation [25] have also suggested new mechanisms for interacting with and examining physical terrain. Yet, despite the popularity of these kinds of models, little research has sought to quantify the degree to which physical representations of terrain improve performance on common map-reading tasks like comparing elevations or assessing lines of sight. In fact, the majority of the research characterizing viewers' ability to make these kinds of judgements (even on 2D maps) predates the advent of modern computational cartography [17][18].

Recently, work on interactive 2D maps has shown that novel interaction techniques like interactive "relief shearing" [27] and viewshed manipulation [14] can considerably improve viewers' ability to understand and interpret complex terrain. However, it remains unclear how these screen-based techniques compare with the experience of exploring a physical model. Our work addresses this gap by comparing the effectiveness of 2D maps, 3D models, and interactive techniques for several fundamental terrain-reading tasks. We also examine the importance of embodied perception and cognition [28] for 3D terrain models, and discuss a variety of ways in which the physical and spatial characteristics of terrain models [12][22] create opportunities for tangible interpretation and interaction [26].

3 MAPS, MODELS, AND VIEWSHEDS

While past research has evaluated the impact of different 2D terrain representations on visibility tasks, the effectiveness of 3D terrain models has not been deeply explored. Moreover, the effectiveness of dynamic viewsheds has not been previously examined for either type of terrain representation. In order to compare each of these approaches, we implemented a set of maps and models that integrate both classical terrain rendering techniques and interactive dynamic viewsheds.

3.1 2D Topographic Maps

As a baseline, we created a simple topographic map (Figure 2) which encodes elevation information using a combination of relief shading and layer tinting. Because prior research by Phillips and others [17][18] has suggested that layer tints support visibility comparison tasks better than other terrain encodings (such as contours and hill shading), we encoded elevation information using hypsometric tints [15]. Specifically, we used a set of continuously progressing tints similar to those favored by Imhof [10], starting with greens in low regions (which tend to have more vegetation) and gradually transitioning to browns for higher regions (which tend to be rocky and alpine).

We created the map based on a roughly 20 km by 20 km digital elevation model of Mt. Sopris, Colorado, which features a number of valleys, ridgelines, and other complex terrain features. The vertical elevation difference between the map's lowest and highest points was approximately 1200 meters. To reduce possible confounds we did not include any lines or symbols such as roads, cities, rivers, or contours. Instead, we only focused on the topographic features and geometric properties of the terrain. We rendered the digital 2D map at a fixed size of 13 × 13 cm on a Microsoft Surface 3 tablet, whose touchscreen is capable of capturing user interactions on the map.

3.2 3D Terrain Models

We also created an 18 × 18 cm 3D printed terrain model of the same region out of white plastic (Figure 3). To provide interactive input and output, we augmented the model with a camera and pico-projector mounted roughly 40 cm above the surface of the model. To detect the position of a viewer's hand relative to the model, we placed a colored marker on the index finger of their dominant hand, then used image processing to transform the x-y

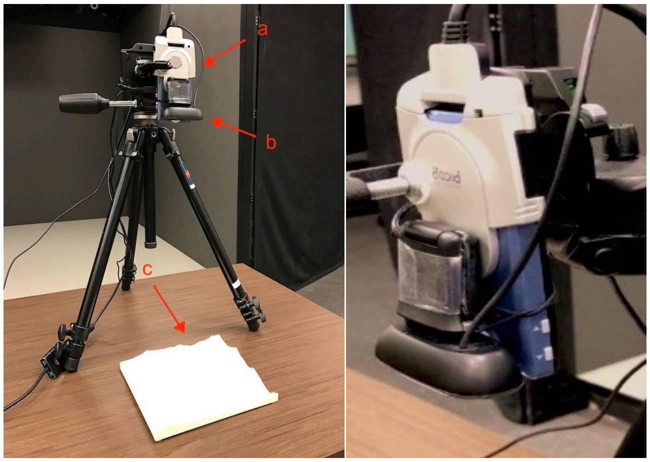

Figure 3: Our 3D tangible map (left) captures user gestures with a webcam (b) and uses a pico-projector (a) to overlay imagery on the physical model (c). Webcam and pico-projector in detail (right).

position of the marker into model coordinates. This setup allowed us to dynamically detect user interactions on and above the model and provide visual feedback similar to that provided by systems like GeoTUI [5] and TanGeoMS [24].

This tracking solution proved to be precise and responsive during our study, and participants experienced no difficulties with interacting with the system. However, because our camera-based tracking system was not as accurate as the touch input on the tablet, we increased the size of the model to 18 × 18 cm to ensure that participants could still precisely indicate points on the model. Both the 2D map and 3D model displayed overlays at the same resolution, and pilot tests indicated that the interaction experience was similar for both.

3.3 Dynamic Viewsheds

In addition to comparing the relative effectiveness of 2D and 3D representations of terrain for visibility tasks, we were also interested in exploring how simple interaction techniques could make these kinds of tasks easier on both types of representations. Specifically, we examined the effectiveness *dynamic viewsheds* overlaid on top of the map or model.

In traditional cartography, the term viewshed [23] describes the geographical area visible from a location, including all locations within line-of-sight, and excluding any that are hidden by the surrounding terrain. Unlike related geographical concepts such as watersheds, viewsheds often include regions that are not geographically contiguous. For example, the viewshed of a mountain peak might contain the peaks of a number of distant mountains, but not the valley floors between them (which might be masked by ridgelines and other terrain features). While dynamic or interactive viewshed analysis is common in geographic analysis and planning tools like ArcGIS [1] and CARTO [4], their use for everyday terrain map tasks has not been deeply explored.

Our dynamic implementation allows viewers to quickly examine the terrain visible from many different locations.

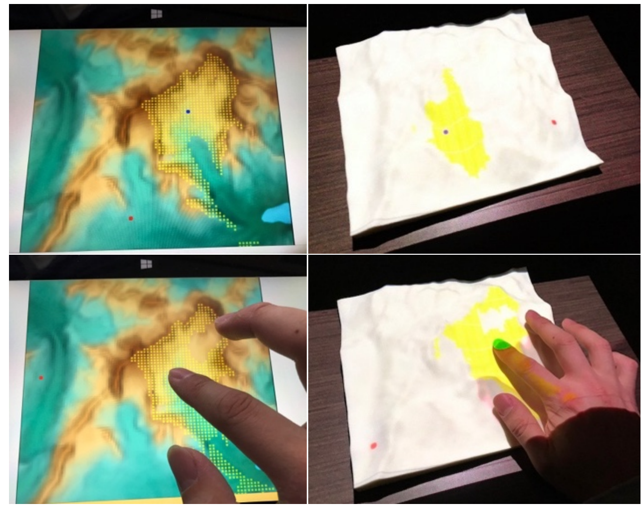

Figure 4: Dynamic viewsheds rendered on the 2D map (left) and the 3D map (right) can manipulated in real-time using touch interactions (bottom left and bottom right).

Touching a point on the map highlights the viewshed for that particular location, instantly revealing all of the locations on the map or model that can be seen from that point. As the viewer interactively slides a finger across the map or model, the viewshed follows their fingertip and updates in real time to show the area visible from that location. This allows viewers to quickly examine the visibility of many different points, and build a better overall understanding of which terrain features occlude others. We render viewsheds on both our 2D maps and 3D models using a textured yellow shadow designed to preserve the legibility of the underlying terrain and layer tints (Figure 4).

4 STUDY DESIGN

The goal of our study was to compare the 2D tablet-based map against the 3D terrain model for visibility-related tasks and to assess the effectiveness of dynamic viewsheds on both representations. To test this, we conducted a counterbalanced within-subjects design study in which we asked participants to complete two different types of visibility tasks using both 2D maps and 3D models, with and without the aid of dynamic viewsheds.

Using mailing lists and fliers, we recruited 20 participants (all students and staff between the ages of 17 and 32) on our university campus. Of the 20 participants, 7 were female and 13 were male. Five had previous experience with topographic maps. Each participant performed a series of short trials and completed a post-study questionnaire. On average the entire process took under 30 minutes. We gave each subject CAD $20 for their participation.

During the study, we asked participants to complete 5 repetitions each of 2 different tasks on both the 2D map and the 3D model. We tested two visibility-related tasks:

1. **Line-of-sight** tasks – where participants must determine whether two locations are visible from one another.
2. **Lowest-visible-point** tasks – where participants must find the lowest point visible from a given location.

Each participant performed both types of tasks using 4 different interface conditions:

1. **2D Map** – a classic layer-tinted topographic map shown on a tablet. This served as the baseline condition.
2. **2D Map + Viewshed** – a layer-tinted topographic map shown on a tablet, augmented with dynamic viewsheds.
3. **3D Model** – a physical terrain model.
4. **3D Model + Viewshed** – a physical terrain model, augmented to support dynamic viewsheds.

Altogether there were 2 tasks × 4 conditions × 5 repetitions = 40 trials (see details below).

We instructed participants to perform tasks in a relaxed and casual fashion, mimicking an ordinary map-browsing process rather than a strenuous map comprehension exam. During each trial, we logged quantitative data such as the task duration and accuracy, along with qualitative observations about participants' interaction strategies and comments. After the 40 trials, each participant completed a short questionnaire probing their familiarity with topographic maps and documenting their reflections on the 2D and 3D representations.

4.1 Task: Line-of-sight

In each *line-of-sight* task, the software highlighted two locations on the map or model and asked participants to determine whether these two locations were visible to one another. (That is, could an observer located at one of the points see the other point?) This prompt replicates traditional line-of-sight tasks often used in cartographic studies [18].

In each trial, the system randomly generated two new locations (at least 3 cm apart on the smaller display) and marked them with red dots. In the two viewshed conditions, the system also automatically displayed the viewshed for one of the two points using a semi-transparent yellow shadow. In all conditions, we allowed participants to examine the model as much as they liked before indicating yes or no by pressing a button on the touchscreen interface.

The addition of a viewshed considerably simplifies line-of-sight tasks, allowing a viewer to determine whether the points are mutually visible by checking whether one point falls within the viewshed of another, without examining the terrain geometry itself. While impractical for most real-world tasks (where the points of interest may not be known in advance by the software) these conditions provide a baseline for understanding participants' performance on the more difficult lowest-visible-point tasks.

4.2 Task: Lowest-visible-point

In the *lowest-visible-point* tasks, the software highlighted a single location (using a red dot) and asked participants to find the lowest location on the map which was visible from that point. This task simulates the more challenging and more common visibility tasks that viewers must routinely perform when navigating or making planning decisions that involve complex terrain. Instead of simply evaluating the mutual visibility of two specific points, viewers must simultaneously assess the visibility of a large number of different points across the map, while also integrating information about their relative elevations.

Again, we allowed participants to interact with the map or model as much as they liked before deciding on a final lowest point. They then indicated their final choice by holding their finger at the desired location and while pressing a button on the touchscreen interface.

5 QUANTITATIVE RESULTS

Following the experiment, we analyzed task duration and accuracy for both tasks (*line-of-sight* and *lowest-visible-point*) across all four conditions (*2D | 3D map*, *2D | 3D map + viewshed*). Data analysis files are attached in the appendix.

During the study, we successfully collected data from a total of 800 trials (40 × 20 participants). In each trial, we recorded two values: the duration in seconds (faster is better) and the accuracy of the participant's input (higher is better).

Due to increasing concerns in a variety of research fields about the use of null hypothesis significance testing [6][7], we analyzed our results using estimation techniques and report effect sizes with confidence intervals (CI) rather than *p*-value statistics. This reporting methodology is consistent with recent APA recommendations [2]. For all durations and error rates we report average participant scores, rather than aggregating across all individual task repetitions. In all cases, we first computed the average score for each individual participant, then computed averages and 95% confidence intervals using these aggregate scores, applying a Bonferroni correction to control for multiple comparisons. Where appropriate, we also computed pairwise differences between conditions, again using 95% confidence intervals with a Bonferroni correction.

5.1 Line-of-Sight Tasks

In the simple *line-of-sight* tasks, participants took an average of 6.25 seconds (CI = [5.22, 7.27]) to determine whether there existed a line-of-sight between the two locations on the plain *2D* map. On the plain *3D* model this number was slightly lower at 5.37 seconds (CI = [4.42, 6.31]). However, with the aid of the *viewshed*, participants were substantially faster – spending on average 3.44 seconds (CI = [2.68, 4.20]) in the *2D + viewshed* condition and 3.95 seconds (CI = [3.26, 3.95]) in the *3D + viewshed* (Figure 5).

Pairwise comparisons show clear differences between the viewshed conditions (*2D + viewshed* vs. *3D + viewshed)* and their corresponding base conditions (*2D* vs. *3D*), but no clear difference between the 2D and 3D representations.

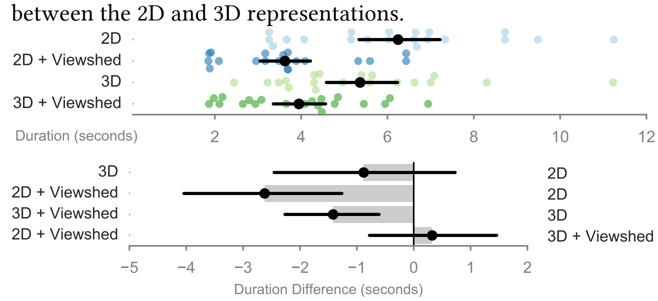

Figure 5: (Top) duration of line-of-sight trials (shorter is better). Each dot shows data from one participant. (Bottom) pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

Participants gave binary Yes / No responses to the mutual visibility questions, from which we computed each participant's average accuracy rate. Although participants performed well in all conditions, the plain *2D* map produced the worst results, with an average score of 83% (CI = [71.1%, 94.9%]). Results for the plain 3D model were higher at 90% (CI = [85.2%, 94.8%]). In the *viewshed* conditions, the number of correct responses was even higher, with 95% (CI = [90.8%, 99.1%]) for *2D + viewshed* and 98% (CI = [95.1%, 100.9%]) for *3D + viewshed* (Figure 6). However, only the comparison between the *3D* and *3D + viewshed* conditions showed a clear difference.

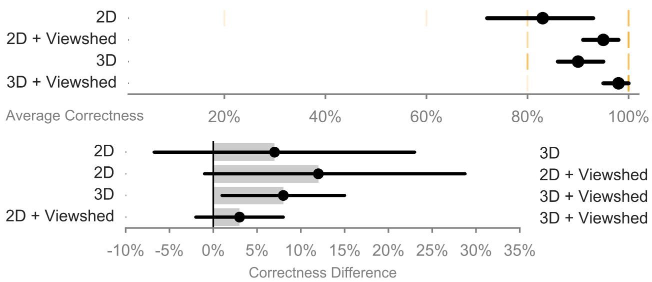

Figure 6: (Top) accuracy of line-of-sight trials (higher is better). (Bottom) pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

5.2 Lowest-Visible-Point Tasks

For the more challenging *lowest-visible-point* tasks, participants generally spent longer. On the plain *2D* map, participants spent 10.79 seconds on average (CI = [8.14, 13.44]), while on the plain *3D* model their average time was 9.55 seconds (CI = [8.22, 10.88]). With the *dynamic viewshed* available, the average duration was 12.76 seconds (CI = [9.25, 16.26]) in the *2D + viewshed* condition and 12.21 seconds (CI = [10.11, 14.32]) in the *3D + viewshed* condition (Figure 7). We saw a pronounced increase in task duration between the results of the *3D* and *3D + viewshed* conditions, with participants generally spending longer when the viewshed was available.

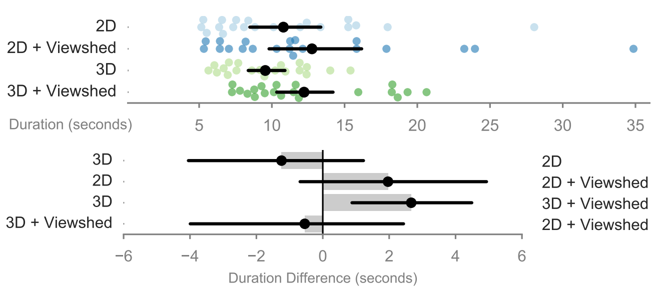

Figure 7: (Top) duration of lowest-visible-point trials (shorter is better). Each dot shows one participant. (Bottom) pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

To measure accuracy in the *lowest-visible-point* tasks, we first assessed whether participants' inputs were valid – that is, whether the point they selected was indeed visible from the initial point. On the plain *2D* map, the average participant chose a valid visible point 84% of the time (CI = [76.8%, 91.2%]), while on the *3D* model the average participant was 85% correct (CI = [77.0%, 93.0%]). However, when using the *dynamic viewshed*, results were better. Participants in the *2D + viewshed* condition correctly identified a visible point 93% of the time (CI = [88.4%, 97.6%]), while participants in the *3D + viewshed* condition identified a visible point 99% of the time (CI = [96.9%, 100%]). In fact, out of 100 total trials, only one participant in the *3D + viewshed* condition chose a point that was not visible from the initial prompt (Figure 8). In pairwise comparisons, the *3D + viewshed* model clearly outperformed both the plain *3D* and *2D + viewshed* variants.

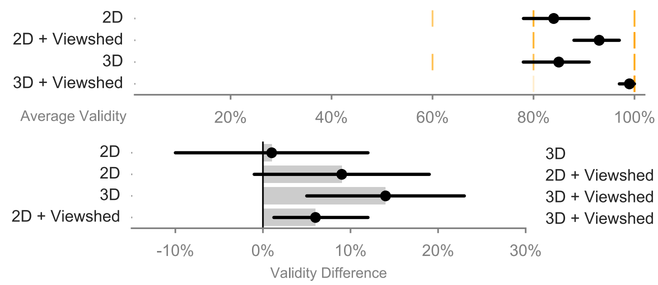

Figure 8: (Top) accuracy (input validity) of lowest visible point trials (higher is better). (Bottom) Pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

Next, we measured accuracy by computing the vertical difference between the point that the participant indicated and the actual lowest visible point on the model. We then normalized these results to compute the error rate as a percentage of the total height of the model. Because of the high resolution of the terrain model, it was often difficult for participants to select the precise point they intended to. As a result, even the correct responses for these tasks typically still include some small amount of vertical error.

When using the plain 2D map, participants' average error ratio was 15.6% (CI = [12.0%, 19.2%]). However, this dropped to 11.4% (CI = [9.1%, 13.7%]) in the *2D + viewshed* condition. On the plain 3D model, average error was 9.6% (CI = [7.9%, 11.3%]) and dropped to 7% (CI = [5.6%, 9.3%]) in the *3D + viewshed* case (Figure 9). In this case, there were clear differences between 2D maps and 3D maps, both in their plain forms (*2D* vs. *3D*) and with viewshed enhancements (*2D + viewshed* vs. *3D + viewshed*).

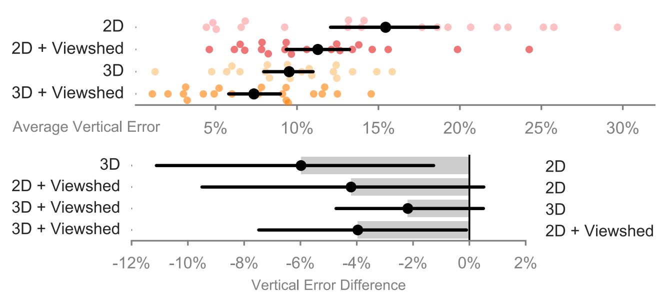

Figure 9: (Top) average vertical error of lowest-visible-point trials (lower is better). Each dot shows one participant. (Bottom) Pairwise comparisons between conditions. Error bars show 95% CIs with a Bonferroni correction.

6 DISCUSSION

For the basic *visibility* tasks, we saw little clear difference between 2D and 3D representations, either in terms of accuracy or task completion speed. However, the addition of viewsheds to both 2D maps and 3D models allowed participants to complete the tasks considerably more quickly and with very high accuracy (see Figures 5 and 6).

For the more complex *lowest-visible-point* tasks, participants were generally more accurate when using the 3D model than the 2D map. We also saw improvements in accuracy with both maps and models that included interactive *dynamic viewsheds* (Figure 8 and 9). In fact, participants were considerably more accurate on average when using the 3D model with dynamic viewshed than when using either 2D interface. However, the accuracy improvements seen in the dynamic viewshed conditions may have come at the expense of a decrease in overall speed, possibly because the dynamic viewshed allowed participants to spend more time extracting additional information to verify their choice.

Takeaway #1: *Dynamic viewsheds make visibility (line-of-sight) tasks easier on both 2D maps and 3D models.* Adding viewsheds resulted in a clear increase in speed for simple tasks and a likely increase in accuracy across both easy and hard tasks.

Takeaway #2: *Combining 3D models and dynamic viewsheds produces the most accurate results.* While both 3D models and dynamic viewsheds individually improved participant accuracy for the visibility tasks in our study, combining the two resulted in the most accurate results across both task types.

6.1 Comfort with 3D Terrain Models

In addition to examining the quantitative differences in performance between the four experimental conditions, we also observed participants' behaviors and strategies when using each of the interfaces. These observations, along with insights from participants' questionnaires, allowed us to more comprehensively characterize how participants used each interface.

In their questionnaires, 6 participants specifically reported that they were more relaxed, comfortable, and confident when interacting with the 3D terrain model than they were with the 2D topographic map. We recruited participants with a broad range of backgrounds and participants' level of confidence with 2D topographic maps varied widely. While some participants were quite comfortable decoding the tint pattern in the 2D map, others visibly struggled to make sense of the color encoding. In one extreme case, a participant (P6) even drew a legend for the tint pattern on a separate sheet of paper (Figure 10) and repeatedly referenced it during the subsequent tasks. (Interestingly, this participant appeared to mistake the hypsometric tints for a bivariate color scale, which may have further impeded their elevation judgments.)

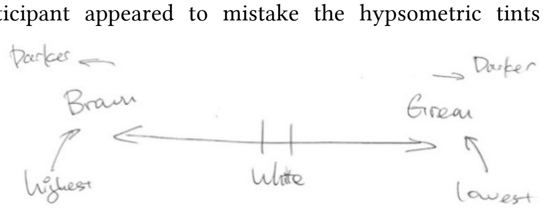

Figure 10: One participate (P6) drew a color spectrum to help interpret the tint pattern on the 2D topographic map.

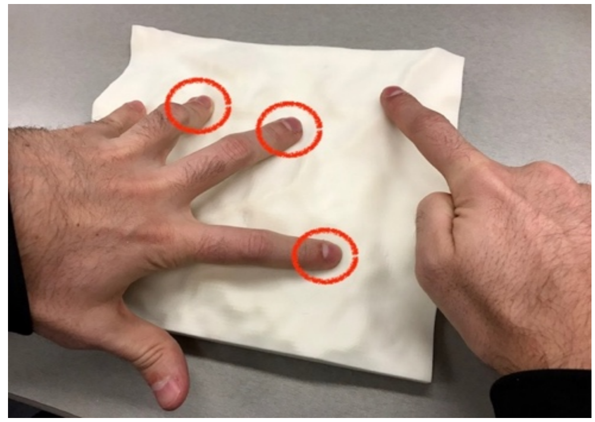

Figure 11: Participants often used multiple fingers to track temporary decisions before reaching a final judgment.

In contrast, no participants struggled visibly with the 3D map representation, and several specifically remarked that they found the 3D terrain model to be "more readable" (P16) and "making much more sense" (P2), because it looks "the same as the real terrain" (P6).

Participants also seemed to find the 3D models to be more approachable. When presented with the tangible model, all 20 participants – regardless of their previous experience with maps and without prompting from the experimenter – immediately began to examine it. Participants moved closer to observe the physical model from various viewing angles and asked questions about various properties of the model. We also observed that most of the participants (16 out of 20) spontaneously touched and manipulated it.

When we asked the participants to compare their personal experience of using the 3D model with their experience using the 2D maps most reported a preference for the 3D version. Four participants specifically noted that the undistorted topography of the physical model helped them to compare and evaluate elevations. Another 3 participants highlighted the fact that the physical model supported additional implicit interaction methods, including head rotation and touch, that they could use to examine the terrain. Others simply remarked that the physical map, especially with dynamic viewsheds, was "cool" (P2, P17, P18), "fun" (P1, P5, P12), and "enjoyable to use" (P6). One participant (P19) even remarked that he could "keep playing with [the 3D tangible map] forever".

Takeaway #3: *Tangible 3D terrain models are more comfortable and approachable than topographic maps, especially to novices.* While we cannot claim generally that 3D models are more readable or legible, many of our participants implicitly and explicitly indicated that they found them to be "less scary" (P11).

6.2 Tracking Temporary Decisions with Fingers

We also observed that many participants (8 out of 20) used the tactile nature of the model to support their thinking and reasoning process. In particular, during the more difficult *lowest-visible-point* tasks, participants often used the fingers on their non-dominant

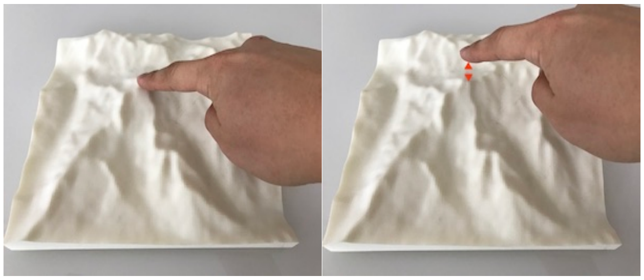

Figure 12: When interacting with the dynamic viewshed, participants either directly touched the 3D map model (left) or hovered above it (right).

hand to track and compare candidate low points. Often, participants would quickly identify and touch several local minima, then compare them to identify the lowest visible point. Participants used up to 3 fingers on their non-dominant hand to track points, often while continuing to search for alternative points using their dominant hand (Figure 11). Interestingly, participants who used this method only used fingers on a single hand to track candidate points – possibly because using touch to compare elevations across two hands would be difficult.

While nearly half of our participants used this strategy with the 3D model, none used it on the 2D map – even though doing so was possible (the 2D map always displays a dynamic viewshed for the location that was most recently touched, ignoring other fingers that remain in contact with the screen). However, we suspect that participants may have anticipated that multi-finger gestures would trigger unpredictable actions on the touch-screen (such as zooming or rotation) as in other tablet-based mapping applications like Google Maps. Moreover, because the touch screen provided no tactile feedback about relative elevations, touching points would only have allowed participants to track candidate locations, rather than compare them.

Because our physical model was small enough to be covered by a single hand, this proved to be an efficient strategy for identifying global minima. However, this strategy may be less effective for larger models, where candidate points may often be too far apart to support tactile comparison.

Takeaway #4: *3D terrain models support tactile comparison which can make it easier to track and verify locations of interest.*

6.3 Touch vs. Hover for Dynamic Viewsheds

Because our 3D terrain implementation displayed dynamic viewsheds based on the x-y position of the index finger on a viewer's dominant hand, it was possible to examine viewsheds either by touching the model directly or by hovering above its surface. Most participants (15 of 20) tended to touch the physical map model through the entire study. When interacting with the dynamic viewshed, these participants kept their fingertip in continuous contact with the physical model. As a result, their experience was similar to using a touch-screen with a non-planar display surface.

However, 5 out of the 20 participants kept their fingertips floating a couple of centimeters above the topographic surface, without direct contact with the map model. Interacting this way, participants experienced no friction on the surface of the model.

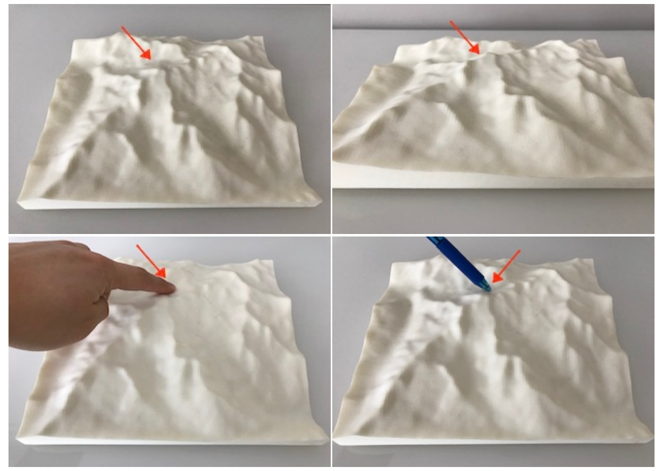

Figure 13: A location on the 3D physical map model with a lower elevation (top left) can be visually occluded by the surrounding topographic features (top right) or by pointing devices like a finger or stylus (bottom).

One participant (P8) specifically emphasized a preference for this "smoother" interaction, which reduced the need to slide fingers across the rough and irregular terrain. Moreover, hovering reduces the amount of terrain occluded by the viewer's finger, including the points directly below it (Figure 12) and may make it easier to see changes to the viewshed.

Participants who used hovering did so only during the tasks that involved manipulating the dynamic viewshed but continued to touch and manipulate the model during the remaining tasks. As a result, we suspect that participants still appreciated the physicality of the topography but preferred hovering over direct touch-control for these kinds of repeated sliding gestures.

Takeaway #5: *Hovering and other off-surface interactions with 3D models can reduce occlusion and may be useful when the surface of the model is rough or irregular.*

6.4 Problems with Touch on Complex Models

We also observed that particularly rough and complex areas of the 3D model (like those highlighted in Figure 13) were sometimes difficult to touch or manipulate directly.

In particular, we observed that concave areas on the model, including steep valleys, were more difficult to reach than peaks and flat areas. While most areas on the physical model we used were flat enough to be accessible to adult fingers, more complex maps with extreme features like pits or steep trenches could make interactions that require direct touch difficult. Steeper and more concave terrain can also cause visual occlusion, in which tall terrain features closer to the viewer hide details behind them.

As a result, participants in our study often needed to adjust their finger positions and viewing angles (sometimes repeatedly) to see and reach a certain part of the terrain model. These observations are consistent with previous research on curved surface interaction [20] and interaction with physical visualizations [12].

Takeaway #6: *Complex 3D terrain models can create visual and physical occlusions that can impede interaction.*

7 DESIGN GUIDELINES

The results of our study indicate that both 3D models and dynamic viewsheds can enhance the legibility of a complex terrain, especially for complex visibility tasks. Based on our observations, we suggest the following design guidelines for future 3D tangible cartography applications.

G1: Use Interactive 3D Models to Encourage Exploration

Our study highlighted how physical 3D terrain models with dynamic viewsheds can help viewers to more quickly and accurately make visibility judgements (***Takeaways #1 & #2***). Moreover, participants found these physical models more comfortable and approachable than 2D topographic maps (***Takeaway #3***). These results suggest that 3D models may be useful for applications that are intended to motivate and encourage non-experts to explore and understand the terrain. Moreover, our experiment shows that dynamic viewsheds can be a clear and easy way to help novices explore and build a deeper understanding of the topography. With this in mind, we encourage designers developing new terrain representations to consider interactive viewsheds as well as other direct and dynamic interactions that can support more detailed inspection and exploration of terrain.

Indeed, 3D physical terrain models are already common in locations like public parks and visitor centers which cater to visitors with little map reading experience (as in Figure 14). As new digital fabrication and shape display technologies make these kinds of maps increasingly easy to produce, we believe they can provide value to novice map readers in a variety of settings.

G2: Support Alternative Physical Interaction Techniques

Participants in our study interacted with physical terrain models in several unconventional ways. Strategies like using multiple fingers to track and compare several points on the model (***Takeaway #4***) embrace the models' tactile and physical potential, while the use of hovering (***Takeaway #5***) highlights the utility of non-tactile interactions even for physical representations. Both 2D maps and physical models may benefit from supporting a range of different interaction techniques – allowing viewers to use a variety of strategies to extract terrain information.

Figure 14: Terrain model at Maligne Lake, Jasper National Park, Canada.

For example, while participants using physical models often used fingers to help track important points on the terrain surface, this strategy could also be useful on 2D maps. As a result, designers creating new 2D terrain representations and interaction techniques may wish to adapt their interfaces to either implicitly or explicitly support multiple passive touches. Similarly, designers of both 2D and 3D map representations should consider the potential benefits of hover interactions (which can reduce both friction and occlusion) in addition to direct touch.

G3: Design 3D Models to Maximize Physical Accessibility

While physical terrain models can be easier to read than their 2D counterparts, they also introduce new interaction challenges such as visual occlusions and complex models may even include unreachable areas (***Takeaway #6***).

With this in mind, we recommend tailoring the interaction methods, as well as the scale and complexity of physical models to maximize physical accessibility. For instance, if the terrain surface has dramatic fluctuations that create pits and trenches that are unreachable with human fingers, increasing the size of the model may be necessary. Hovering interactions, or interaction with a stylus or other pointing implement with a more precise tip, may also help mitigate these issues. For maps that are intended to support situational awareness, flattening the terrain to reduce visual occlusion may also be beneficial.

8 LIMITATIONS AND FUTURE WORK

While our study included participants with considerable variation in map-reading experience, few had any formal training and none used topographic maps regularly in a professional context. Determining whether tangible models provide the same benefit for expert map users requires additional study. Moreover, because we used maps and models of only one area, it is difficult to know whether participants' performance and strategies would apply equally to all types of terrain. While 3D models performed well for mountainous terrain with complex and steep geographical features, they may provide less of a benefit in flatter regions. Further work is necessary to characterize viewer performance for a diverse range of terrain types including flat and rolling regions, strong concave features like canyons, and more abrupt elevation changes like those found in urban environments.

Finally, hand-sized models like the one we used in our study support a number of map reading strategies (like using fingers to track possible low points) that may not be possible on larger (Figure 15) or smaller displays. Additional studies may be necessary to assess the generalizability of these techniques for maps of varying sizes.

9 CONCLUSION

In this paper, we presented a study comparing the utility of 2D topographic maps and 3D terrain models for visibility and line-of-sight tasks. We also examined the impact of dynamic interactive viewsheds on both types of representations. Our findings show that augmenting 3D models with dynamic viewsheds improves

Figure 15: We consider hand-sized terrain models (left), rather than larger terrain models (right) where direct touch interactions can be more difficult.

performance for both simple and complex visibility-related tasks. Based on these findings, we contribute design guidelines of new tangible and interactive tools that can make the process of examining and understanding terrain more natural and engaging. In doing so, we hope to set the stage for a variety of new physical and interactive cartographic tools.

ACKNOWLEDGEMENTS

We are very grateful to the Foundation CMG / Frank and Sarah Meyer Collaboration Centre for enabling our research. The work was supported by the NSERC / AITF / Foundation CMG Industry Research Chair program in Scalable Reservoir Visualization at the University of Calgary.

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