TerraGuide: Design and Evaluation of a Multi-Surface Environment for Terrain Visibility Analysis

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ABSTRACT
Terrain visibility analysis is a challenging task that is currently supported by complex digital tools with cumbersome interfaces. In this paper, we present TerraGuide, a novel multi-surface environment for exploratory terrain analysis. TerraGuide provides three tightly coupled displays including a real-time viewshed, a 3D panoramic view, and a helicopter view controlled by an optically tracked tablet. A user study compared these techniques and identified users' strategies in solving a complex terrain analysis problem. Users overwhelmingly adopted a bi-manual use of the tabletop viewshed and tablet-based helicopter techniques. This paper gives insight into how multi-surface environments can be designed to allow complementary use of and fluid switching between techniques.

Author Keywords
Multi-surface environment, digital tabletop; terrain analysis

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

INTRODUCTION
Activities such as urban planning [23], military command and control [3,22], wildlife observatory design [10] and search and rescue [1] require line-of-sight analysis of physical geography. For example, an urban planner may wish to know the effect on the skyline of constructing a new apartment building, while a mobile systems engineer may wish to determine the highest-coverage locations for a set of cellular transmission towers. People find terrain analysis difficult because it requires them to construct a mental model of 3D geography from representations such as a 2D map [14].

CHI 2015, April 18–23, 2015, Seoul, Republic of Korea.

ACM 978-1-4503-3145-6/15/04…$15.00.
http://dx.doi.org/10.1145/2702123.2702480

Simple 3D visualization of terrain is not sufficient on its own, since terrain analysis problems may require an understanding of line-of-sight from multiple locations simultaneously. For example, picking the best location for a group of cell towers requires an analyst to understand the combined coverage of a set of candidate locations. In general, terrain analysis requires the analyst to answer questions such as "What places are visible from the given set of observation points?" and "How many places is the given location visible to?" [14]. Despite the development of new digital technologies for terrain analysis, universities can devote entire courses to this problem (e.g., [16]).

Traditionally, terrain analysis is performed using paper maps where contour lines and shading show terrain elevation. Acetate sheets are placed over the maps and are annotated using pens. More recently, Geographic Information Systems (GIS) use digital representations of maps, permitting special-purpose visualizations for terrain analysis. These include viewshed visualizations [17], line-of-sight tools [5], 3D panoramic views [10], and magic lenses [4]. Current GIS visualizations often suffer key usability problems, however, hindering their adoption. For example, the ABACUS military simulation tool [20] can

Figure 1. TerraGuide. The interactive tabletop provides the user with a 2D top-down view of a 3D terrain. Viewsheds show visibility from a source point. A secondary display shows a panoramic view. A hand-held tablet displays terrain in 3D.

show a 3D panoramic view from a given map location, but requires a multi-step dialogue box and several seconds to generate the view. Additionally, line-of-sight visualizations are typically decoupled from the underlying map view, making it difficult for users to move quickly between the map and the visualization [5,6,10].

In this paper, we address the problems of terrain analysis through a novel multi-surface environment. Our TerraGuide tool centres on a digital map presented on a digital tabletop surface, augmented by a large screen secondary display and a hand-held tablet (Figure 1). Three techniques aid with terrain analysis: a *viewshed* shows visibility in a cone drawn from the user's touch point on the table; a *panoramic view* provides a 3D first-person view on a separate display, and a *helicopter view* allows the user to see terrain in 3D on a handheld tablet positioned over the table. Previous systems have demonstrated visualizations similar to these; the novelty of TerraGuide comes from the real-time and fluid combination of these interaction techniques.

We have performed an exploratory study evaluating TerraGuide and its use. The first part of the study evaluated performance, user preference, user confidence and cognitive load in performing a simple analysis task with combinations of the different techniques. The second part determined the strategies that people used when performing a more complex task. Interesting results included that the use of the 3D panorama view worsened task completion time and did not improve error, yet increased participants' confidence in their analysis; that the viewshed technique was widely used for detailed analysis; and that the dominant strategy was bi-manual use of the viewshed and helicopter techniques.

Our central contribution is to show how interaction techniques on multiple surfaces can be designed to allow fluid, combined use of multi-surface techniques and easy change between these techniques. Our results are of interest both to designers of systems supporting terrain analysis and to designers of multi-surface environments in general.

The paper is structured as follows. First, we review the problem of terrain analysis. We then introduce TerraGuide and explain the principles behind its design. Finally, we report our study evaluating TerraGuide's multi-surface approach, and conclude with lessons for designers.

TERRAIN ANALYSIS

Tools to aid terrain analysis have evolved from paper maps to interactive, digital models. In this section, we describe what terrain analysis is and why it is complex, and report on existing terrain analysis tools.

Terrain and Visibility Analysis

Terrain analysis is the process of interpreting geographic features to predict the effect of the terrain on relevant operations. Within this domain, *visibility analysis* focuses on line-of-sight and visibility. Visibility analysis is used in siting communication towers [19], military planning [14], archaeology [29] and urban planning [23].

For example, terrain analysis is critical to military planning. The US Army field manual states, "*Weather and terrain have more impact on battle than any other physical factor, including weapons, equipment or supplies*" [28]. Analysis of terrain is useful in designing defensive positions (to ensure that all avenues of attack are covered), and in planning safe routes for mobile forces (reducing visibility to hostile forces.) [11]

Visibility analysis requires considerable expertise [14]. Tools used have become sophisticated, often leading to complex user interfaces [6]. University courses and certificates are offered on the subject of learning how to perform terrain analysis (e.g., [16]). Visibility analysis is a cognitively challenging process involving the projection a 2D map representation of the terrain into a 3D mental model [14]. The analyst then must mentally query their terrain model to answer questions such as "how much of the map do these cellular towers cover?", or "from what parts of the town is this new apartment building visible?"

Existing Techniques for Visibility Analysis

Existing visibility analysis techniques have been developed within specialized tools for military planning, and as part of more general geographic information systems (GIS). Techniques were initially developed around paper maps, more recently evolving to sophisticated digital tools.

Paper Maps and Contour Lines

A contour line on a paper map denotes terrain of equal elevation. Multiple contour lines on a map can convey the shape of the terrain. Features of contour lines such as line weight, colour, type, and numbers can show additional information such as the elevation as a number [26].

When trying to find a safe route for vehicles through a combat zone, a military planner might use a contour map overlaid with an acetate sheet. The planner draws the route on the acetate with a marker, using the contour lines to visualize the visibility of vehicles following the route. This requires an ability to extract a mental model of the terrain from the map representation, a cognitively demanding task requiring significant expertise [14].

Digital Maps and Tabletops

Digital maps have enabled powerful tools to assist terrain analysis. Using digital elevation models, algorithms can determine line-of-sight information and generate 3D models of terrain [14]. Digital maps allow for user interaction such as showing and hiding information layers (e.g. population) and changing the scale of the map [7].

Multi-touch tabletops have also been proposed for map-based tasks, bringing advantages of a large space over which to view the map, and natural support for collaborative discussion of the map's content [3]. Recent

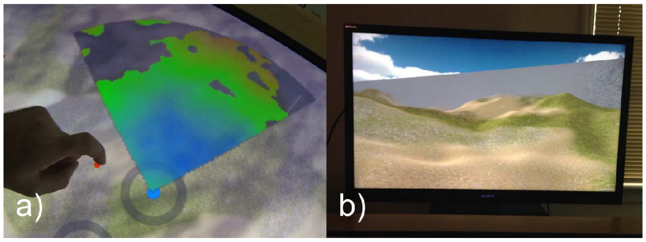

Figure 2. a) Colour-mapped elevation viewshed. b) The corresponding panoramic view.

tabletop tools such as Skyhunter [4] and DIGTable [15] allow users to explore the geographical properties of maps.

Mixed reality systems have been proposed to combine large displays with familiar physical devices for terrain analysis. Thumbles [18] provides physical pucks under robotic control to help with complex spatial layout problems such as telecommunication tower positioning. Thumbles is not intended to support general terrain analysis.

Interaction Techniques

Several interaction techniques have been developed for terrain visualization. The *viewshed* interaction technique shows what parts of the terrain are visible from a specific location on the map (Figure 2.a) [17]. Viewsheds are traditionally displayed as a 2D arc (pie slice) where visible terrain in shown in one colour and invisible terrain is shown in another colour. The viewshed tool provides answers to questions such as, “What places are visible from the given observation point?” and “How many places is the given observation point visible to?”

Viewshed tools in existing systems are typically cumbersome to use, requiring multi-step dialogues to specify and lengthy rendering times. For example, the viewshed tool in the popular GIS ArcGIS [30] takes seven parameters to operate, and depending on the task and computer hardware can take minutes to compute [10].

Panoramic views generate a 3D view of the terrain from a given perspective. 3D perspectives of digital terrains have been shown to give a better understanding of the shape of terrain and are generally preferred by users [10,13,24]. However, previous studies were performed with static images of 3D terrain and did not allow real-time updates. There has led to continuing debate on the types of analysis tasks that benefit from 3D perspectives [24].

Panoramic views and viewsheds can be complementary. For instance, when looking analyzing the Rocky Mountain landscape, Germino et al. found that 2D viewsheds were superior for quantifying the *dimensions* of a terrain (i.e. areal extent, relief, depth), while computer-generated 3D panoramic views at ground level performed better for representing the *composition* of a terrain (i.e. land cover, diversity, edge) [10]. The BUILD-IT system allows designers to view a virtual 3D representation of their workspace through a vertical display [8]. In the ABACUS military simulation tool, analysts can use the panorama tool to generate a soldier’s first-person view [20]. Users must navigate a cumbersome dialogue to specify the desired view and then wait through a slow rendering phase.

Recent projects have used *tablets* to aid geospatial exploration and analysis. In Skyhunter, the user places a tablet on a tabletop to visualize seismic information corresponding to the geographic location underneath the tablet [4]. Tablets can act as Magic Lenses [2] to allow for the exploration of a 3D space or volume [25]. For example, the metaDesk [27] system uses a tethered arm-mounted magic lens to display a spatially contiguous 3D view of the MIT campus. Tablets have been shown to work well for exploring a 3D volume in combination with tabletops [25] when portability is important [4].

TERRAGUIDE

Existing digital tools for terrain analysis have made considerable advances over traditional paper-based approaches, allowing easier manipulation of maps using panning, zooming and providing visualizations such as viewsheds and panoramic views to aid analysis. However, existing systems fall short of integrating these tools in a fluid and fast experience. We have developed TerraGuide to explore how a multi-surface environment can allow users to easily combine different views of a terrain, allowing quick analysis where different interaction techniques are fluidly used in concert.

As shown in Figure 1, TerraGuide is composed of three surfaces: a large interactive tabletop, a vertical TV screen and a multi-touch tablet. The tabletop displays a top-down (planimetric) map. The user can move and rotate a number of viewshed widgets on the tabletop. A vertical display is located across from the user, and shows a panorama view from a first-person perspective. A tablet displays a *helicopter view,* showing parts of the terrain in a 3D view. We now describe the different views provided by the system, and how they are designed to fluidly work together.

Viewshed

TerraGuide includes a touch-based interactive widget implementing the viewshed visualization (Figure 2.a). The user places a viewshed anywhere on the terrain simply by touching and dragging it to the desired location on the 2D map. The viewshed can be rotated using a disk located around the widget. Viewsheds can be hidden (to reduce clutter) and revealed by tapping on the widget. In addition to visibility information, the viewshed displays elevation through a colour gradient. As in traditional terrain analysis applications, blue is mapped to low elevation, green to medium, and red to high elevation.

Unlike existing tools [10], TerraGuide’s viewshed is rendered in real-time as it is dragged across the table. This is possible through a fast viewshed computation algorithm [17], and using an adaptive resolution where the viewshed is drawn in the best resolution possible while moving and high resolution while stable. This transforms how the viewshed can be used, allowing exploration of terrain visibility with simple dragging, as opposed to the careful planning of viewshed position required by traditional tools.

Panoramic View

In TerraGuide, the panoramic view is shown on a secondary display in front of the table (cf. vertical screen on Figure 1). It shows a 3D representation of the viewshed from a first-person perspective. The panoramic view shows the terrain from the origin of the viewshed, in the direction in which the viewshed is pointing. As the viewshed is moved or rotated, the panorama view updates in real-time. Points in the panorama view beyond the range of the viewshed are shown in grey fog to mimic distance limits in visibility, e.g., due to limits of human sight or transmission distance of a cellular tower.

Tablet-Based “Helicopter” View

A hand-held tablet shows a 3D view of the terrain in the style of a Magic Lens. Users can move the tablet over the table, and see the terrain as it appears from the perspective of the tablet’s position and orientation. Moving and rotating the tablet changes the point of view of the 3D visualization that it displays. Intuitively, the tablet acts as a helicopter view, which the user can move around, to view the terrain from different angles.

The tablet view is synchronized with the tabletop, showing the terrain as it would appear if it rose in three dimensions from the table’s surface. E.g., if the tablet is held obliquely to the table, it shows a panorama view similar to that of the secondary display. This allows quick exploration of terrain features by moving and rotating the tablet.

Rapid, Coupled Operation with Ease of Switching

The design of TerraGuide followed three principles. Views should be computed in real-time, allowing rapid exploration of the terrain without complex dialogues or noticeable rendering times. As discussed by Field et al. [9], the views on different surfaces should be tightly coupled, allowing them to be easily used in concert. In TerraGuide, all views are updated in real-time using simple interaction based on touch and hand motion. And finally, it should be easy to switch between views without loss of context or overhead of correlating information between the views.

As we have discussed, the views are coupled in two notable ways. First, the panoramic view is slaved to the last-used viewshed widget. A viewshed represents visibility and elevation information from the point of view of its origin. The panoramic view shows a first-person view of the terrain. As the widget is dragged or rotated, the panoramic view is updated. Therefore, a single touch-based drag or rotation controls both displays. This is significantly different from existing approaches where panoramic views are created explicitly using dialogues. Second, the tablet-based helicopter view is directly coupled to the map on the table, providing a 3D window onto the 2D table. Ease of switching between views is primarily supported by the tight coupling between the views, helping users retain context.

Implementation

TerraGuide was developed in C# using the Unity game engine. Views are synchronized using the Janus networking toolkit [21].

EVALUATION

TerraGuide was designed to allow people to fluidly move between different views represented on different surfaces, using whichever is most appropriate to their task. We intended that the combination of views and interaction techniques would enhance users’ ability to perform terrain analysis tasks, and that the tight coupling of the views on the three surfaces would enable effective use of all three in concert. To determine whether these goals were met, we performed a user study consisting of two parts. The first assessed the effectiveness of combinations of the three techniques on task performance, user confidence and task load. The second involved an open-ended task to investigate users’ strategies and preferences when using the three techniques together. This study led to interesting discoveries, such as that the overwhelmingly dominant strategy in the open-ended task involved the bi-manual use of the viewshed widget and the tablet helicopter view, and that the panoramic view increased users’ confidence in their results, but did not improve their task performance.

Participants

We recruited 26 participants over the age of 18 (16 male, 10 female) from Queen’s University. All participants regularly used touch devices. Part 1 took 25 minutes on average and part 2 took 15 minutes on average to complete.

PART 1: EFFECTIVENESS OF TERRAGUIDE TECHNIQUES

In the first part of the study, participants solved a simple terrain analysis problem using three different conditions: (1) viewshed only, (2) viewshed with panoramic view, and (3) viewshed with tablet view. They were trained on each condition with a practice map before starting the trials. Participants were instructed in how to use each technique and were allowed to practice until they felt comfortable using the system. Each condition was performed three times in a row on different maps for a total of 9 trials (12 including training). The conditions for task 1 were counter-balanced to reduce the impact of learning effects.

Task: Finding the Lowest and Highest Points

Participants were asked to perform a simple terrain analysis task, finding the highest and lowest points on a given terrain. To complete the task, participants dragged a red and a blue pin to what they thought was the highest and lowest locations on the map. Once satisfied with their placement of the pins, they indicated that the task was complete. Immediately after each trial they were asked to score their level of confidence in the correctness of their results. Participants completed questionnaires for each condition.

Measures

We assessed each condition based on: *completion time:* the time from the start of a trial until the participant specified he/she was done; *error:* the difference in heights between the participant's chosen points and the actual highest and lowest points on the map; *user confidence:* on a Likert scale ranging from 1 (no confidence) to 5 (fully confident); and *cognitive load:* measured through the NASA-TLX [12].

Apparatus

The interactive tabletop consisted of a 55" Sony television with a PQ Labs G4S infrared frame. The external vertical display was a Sony 46" television. A Microsoft Surface 2 provided the tablet view, which was tracked using four V100:R2 OptiTrack cameras.

Results

Our results compare the three conditions sets: viewshed alone (*ViewshedAlone*), viewshed and panorama view (*ViewshedPano*), and viewshed and tablet (*ViewshedTab*). We now summarize these results in terms of task completion time, error, confidence and cognitive load.

Task Completion Time

We defined completion time as the time it took each user to complete the task in seconds. A one-way within-subjects ANOVA was conducted with the factor of technique-set. The results indicated a significant effect on completion time, Wilk's Lambda=.68, $F(2,24)=5.76$, $p<.01$, multivariate $\eta^2=.32$.

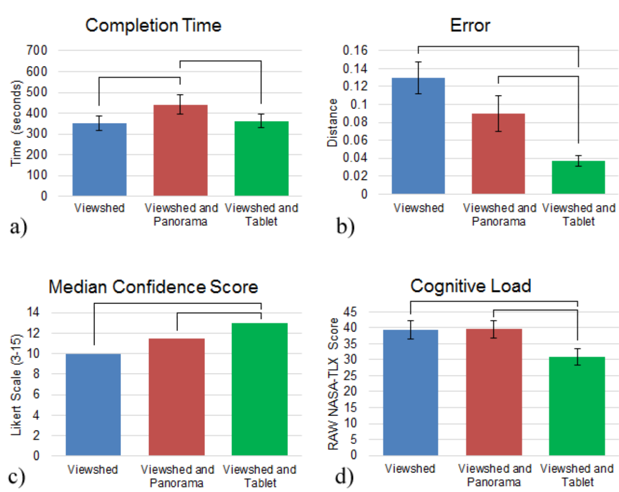

Figure 3. Graphs showing the techniques' performance in a) completion time, b) error, c) median confidence summing results of three trials, and d) cognitive load. Error bars show standard error and hats indicate significant difference.

A paired-samples *t*-test with a Bonferroni adjustment was conducted to evaluate effects on completion time. The mean completion time for *ViewshedPano* (M=441.6, SD=231) was significantly longer than *ViewshedTab* (M=362.3, SD=164.2, d=.4), $p<.03$, and *ViewshedAlone* (M=353.1, SD=175.5, d=.4), $p<.01$. I.e., participants were slower when using the *Panorama* view than when using the *Tablet* or *Viewshed* alone conditions (Figure 3.a). Cohen's d suggests a moderate effect size on this slow-down.

Error

A one-way within-subjects ANOVA was conducted with the factor of technique-set. The results indicated a significant effect on error, Wilk's Lambda=.42, $F(2,24)=16.4$, $p<.01$, multivariate $\eta^2=.58$. A paired-samples *t*-test using Bonferroni adjustment indicates that the mean difference in error when using *ViewshedTab* (M=0.037, SD=0.03) was significantly less than when using *ViewshedPano* (M=0.09, SD=0.1, d=0.71), $p<.02$ and *ViewshedAlone* (M=0.13, SD=0.09, d=1.4), $p<.01$ (Figure 3.b). Cohen's d shows a moderate to strong effect.

That is, using the tablet view together with viewshed, participants were able to find the highest point with significantly less error than when using the viewshed and panoramic view or the viewshed alone.

Confidence

Confidence was based on the participant's response to: *"Indicate the degree of confidence you have in the placement of your flags",* using a scale of 1 (no confidence) to 5 (full confidence).

A Friedman test was conducted to evaluate differences in medians among the confidence levels when using *ViewshedAlone* (MD=10), *ViewshedPano* (MD=11.5), and *ViewshedTab* (MD=13). The test was significant, $\chi^2=18.24$, $p<.01$. The Kendal coefficient of concordance was .351, indicating moderate differences between the three conditions. Follow-up pairwise comparisons were conducted using a Wilcoxon test. The median confidence level for *ViewshedTab* was significantly higher than for *ViewshedPano* ($p<.02$) and *ViewshedAlone*, ($p<.01$). Also, participants were significantly more confident using *ViewshedPano* than *ViewshedAlone* ($p<.01$).

In sum, participants were more confident when using the panorama view and viewshed than when using the viewshed alone, and more confident yet when using the tablet and viewshed (Figure 3.c).

Cognitive Load

Cognitive load was based on NASA-TLX [12] scores for each of the technique sets. A one-way within-subjects ANOVA was conducted with the factor of technique set. A significant effect was found on cognitive load, Wilk's Lambda=.4, $F(2,24)=17.74$, $p<.01$, multivariate $\eta^2=.6$.

A paired-samples *t* test using Bonferroni correction indicated that the mean cognitive load for *ViewshedTab* (M=30.97, SD=13.3) was significantly lower than for *ViewshedPano* (M=39.53, SD=14.5, d=0.6), p<.01 and *ViewshedAlone* (M=39.38, SD=14.1, d=0.6), p<.01. Further, the Cohen's d suggests a moderate to high effect.

That is, participants' cognitive load was significantly lower when using the tablet and viewshed combination than when using the viewshed alone or the panorama view together with the viewshed (Figure 3.d).

Discussion

The results clearly show that the tablet plus viewshed condition outperformed the other two conditions. The presence of the tablet increased participants' confidence in their results, while reducing error and cognitive load. The use of the tablet had no effect on task completion time. This indicates that participants were able to successfully interpret terrain data using the tablet's "helicopter" view, and that any disadvantage in having to use two surfaces to solve the task was outweighed by the advantages the two views conferred.

Conversely, the presence of the panorama view did not enhance participants' performance. Compared to the viewshed alone, adding the panorama offered no improvement to error or cognitive load. Task completion time was worsened. Interestingly, participants' confidence in their results improved, despite the fact that their error did not improve.

With the viewshed alone, participants were able to complete the task as quickly (or quicker) than the other conditions, despite only approximately 10 minutes of training on what to them was a new interaction technique. This also implies that the viewshed is usable by non-experts.

PART 2: STRATEGIES IN REALISTIC TERRAIN ANALYSIS

In the second part of the study, participants were asked to use all three techniques (viewshed, panoramic view, and tablet) at the same time in a more complex terrain analysis task. The participants and apparatus remained the same as in part 1. Participants first familiarized themselves with the system by solving a sample task on a training map. They then completed the task six times on different maps.

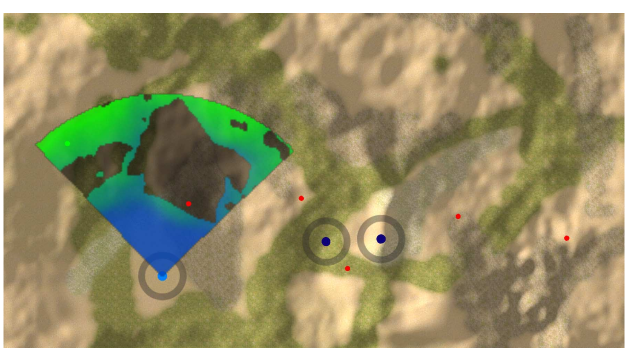

Figure 4. User placing a watchtower (viewshed) to cover the red points of interest. Note the green point on the left of the viewshed indicating the point is in line-of-sight of the tower.

Task: Watchtower Positioning

Participants were instructed to place three watchtowers around a terrain to cover six points of interest. This task required them to synthesize information over the entire map. As seen in Figure 4, a "watchtower" was represented by a viewshed widget and a "point of interest" was represented by a red circle on the terrain. The point of interest changed colour from red to green when it was in line-of-sight of a watchtower.

Procedure

Participants completed the task six times on six different maps. We video-recorded all trials. Following the session, participants completed a custom questionnaire to assess their preferences, and participated in a semi-structured interview.

We used an open coding process to analyze the videos and identify behaviours and events. Of the 26 participants, 25 videos were collected. One participant's video was not recorded due to technical difficulties. We randomly chose videos from 10 of the 26 participants for detailed coding, representing 22 minutes and 17 seconds of video. From these 10 videos, common strategies were determined. Two researchers performed less detailed video coding on the remaining 15 videos in order to identify instances of these common strategies. Conflicts were resolved through discussion between the researchers performing the coding.

Our detailed video coding followed the scheme showed on Table 1. Each action was coded over 3 dimensions: technique used, action type and the body part involved. Example events were *Viewshed 2 macro movement with left hand*, or *Panorama looked with head*. The action type dimension specifies the type of manipulation executed by users. For example, *Micro* and *Macro* distinguish between small versus large movements of a viewshed.

We coded interaction with the fourth map completed, allowing the participants enough time to have determined a preferred strategy. This map was difficult enough that it could not be solved moving around viewsheds randomly and hoping to find a solution by luck, but required actual analysis of the terrain.

Technique Used	Viewshed (1,2,3), Panorama, Tablet
Action Type	Micro, Macro, Rotate, Search, Still, Look
Body Part	Head, Left Hand, Right Hand

Table 1. Dimensions of coding scheme.

Strategy Name	Num. Users	Sweeping
Bi-manual viewshed/tablet alone	11	0
Table first then bi-manual viewshed/tablet	8*	8
Tablet first then bi-manual viewshed/tablet	6	1

Table 2. Number of participants using each strategy. *Two of eight participants put the tablet down to use the viewshed.

Results

Our detailed video coding revealed that participants took on average 2 minutes and 13 seconds to complete the task (*SD*=94 seconds). They switched frequently between techniques, on average 13 times throughout the task (*SD*=9). The table was used on average 6.6 times during the task (*SD*=4.3), or 71% of total time; participants physically interacted with the viewshed widgets for on average 59 seconds per trial (*SD*=41), representing 57% of their total time. The tablet was used 5.4 times on average (*SD*=3.9), or 28% of total time. Finally, the panoramic view was used 0.9 times on average (*SD*=2), representing 1% of total time.

Our results showed a dominant strategy of bi-manual use of viewshed and tablet. Minority uses involved first using the tablet for an extended period, or using the table first for an extended period, before switching to the combined viewshed/tablet strategy. The distribution of these strategies over participants is summarized in Table 2. With both the viewshed and the tablet, participants frequently adopted a sweeping motion, allowing real-time exploration of the terrain. Questionnaires showed a clear preference for tablet over the panoramic view. In the next section, we detail the strategies we observed and report participants' preferences.

Bi-Manual Viewshed and Tablet

23 of 25 participants adopted a bi-manual strategy, where they used the viewshed with one hand, and the tablet with the other, shifting their view between them. Figure 6 shows an

Figure 6. Participant demonstrating bi-manual use of the tablet and viewshed.

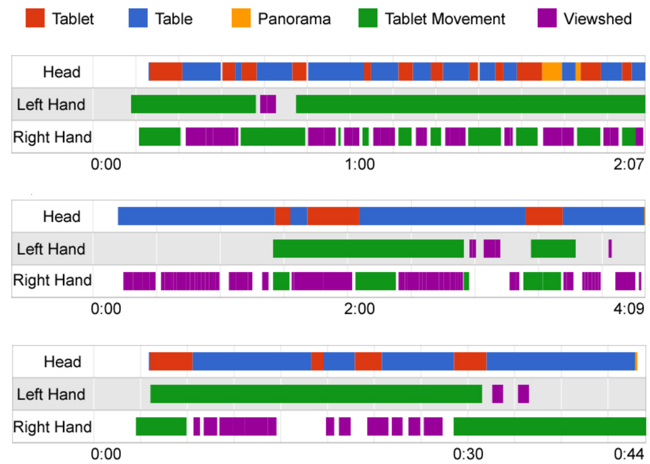

Figure 5. Strategies: a) Bi-manual; b) Table-first, then moving between tablet and viewshed – note two-handed use of tablet; c) Tablet-first, then bi-manual.

example of this strategy. Participants switched between attending to the viewshed and the tablet on average 12.1 times when performing the task. The table was used for intervals of 16.1 seconds on average, while the tablet was used in intervals of 6.5 seconds on average. An example of a video coded bi-manual strategy is shown in Figure 5a.

The remaining two participants used a variant of the bi-manual strategy. Rather than holding the tablet in their hands while interacting with the viewshed, they instead placed the tablet on the wooden edge of the table when using the viewshed, then picked the tablet up and used it with both hands, then put it down again to return to the viewshed. This variant moved back and forth between the interaction techniques, as with the truly bi-manual strategy.

The bi-manual approach allowed participants to see detailed visibility using the viewshed together with the 3D perspective of the tablet view. Participant 24 explained, *"I started off with the tablet, seeing where the points were. Then I tried a couple points with the viewshed, I'd see if I could actually see the points from where I thought I could with the tablet. If I couldn't, I'd either try fine-tuning it if I could, or I'd use the tablet again to see if there were any other points I could use."*

Table-First

Eight of 25 participants used a *Table-first* approach where they used the table for an extended period at the start of the task. On average, these participants used the table for 74 seconds before moving to the bi-manual strategy.

Some participants adopted this strategy in hope of completing the task without actually analyzing the terrain. Users swept the viewshed around, hoping for a solution. Participant 0 explained, *"I decided the distribution of the points where I would put the viewsheds, and then by chance see if I could get it, then if I couldn't, I would use the tablet to see if there is a mountain close by it could go on top of, or* *see why they're hidden."* Our map was sufficiently complex that this strategy did not work, forcing participants to change strategy (for 6 participants to bi-manual, and for two to the strategy of moving between tablet and viewshed, but holding the tablet in both hands when in use – an example of the latter strategy is shown in Figure 5b). Participant 10 explained: *"Initially I tried with just the viewshed, and then once I realized that it was really important to be able to see depth, I just started using the combination of the viewshed and the tablet."*

Tablet First

Six participants used a *Tablet First* strategy, involving an extended use of the tablet at the beginning of the task. These participants used the tablet for 15 seconds on average before switching to the bi-manual strategy (Figure 5c).

Participants reported that the tablet was easy to use and aided navigation through the terrain. Participant 0 stated, *"I liked the tablet because I could do a quick sweep of the terrain, and then I understood what I was looking at as a whole"*. Participant 16 said: *"The motion tracking made it really intuitive to use."* Participant 11 commented on the tablet's ease of use: *"The tablet was the best. It's a lot easier to see when you can just move the tablet around."* These comments are consistent with our findings from task 1 that the use of the tablet reduced users' cognitive load.

This strategy allowed users to get a big-picture view of the terrain. Participant 18 stated, "*[I used it] for getting a general lay of the land. It really helps in an intuitive sense to figure out where you have hills or valleys, where you are going to have the most occlusion."* Participants then moved to the bi-manual approach, already having ideas of potential locations for success and areas to avoid.

Panoramic View

These three strategies indicate the success of the viewshed and tablet views. The panoramic view, on the other hand, received minimal use, accounting for only 1% of the participants' time. In interviews, participants complained about discomfort when using the panoramic view. Participant 9 commented, *"I felt really dizzy"* and, *"It gave me a headache, and I felt that it was easier to see where I want to place my towers using the tablet"*.

The panoramic view was located in front of the participant, showing the terrain from the perspective of the viewshed. Therefore, the orientation of the panoramic view did not always match the orientation of the participant, requiring the participant to mentally reorient the view on the terrain to match that of the panoramic view.

Participants found that the tablet provided similar information to the panoramic view, but more effectively. 16 stated that they felt the panoramic view was not useful when the tablet was available. Participant 8 said, *"The tablet kind of made the panoramic view a little bit useless."* Participant 23 said, *"I could get all the information provided by the panorama on the tablet, but faster."*

Viewshed Sweeping

Nine participants displayed a *sweeping* behaviour with the viewshed where they made large circular movements around an area of interest. Nine participants used sweeping an average of 3.2 times each (*SD*=2.8). As shown in Table 2, all eight participants that used the *Table First* strategy also used the viewshed sweeping behaviour. One participant used sweeping during a *Tablet First* strategy. By taking advantage of the real-time nature of the viewshed widget, participants were able to quickly sweep the terrain to get a general sense of its elevation. Participant 0 explained, "*I would do a quick sweep with the viewshed, then I had a couple areas that I was interested in"*

Participant Preferences

Participants indicated their preferences through questionnaires. The majority felt that the viewshed alone would have been sufficient to carry out the task. When asked: "*Do you think you could have completed part 2 with the viewshed alone?*" 5 of 26 participants answered "*Yes*" and 21 answered, "*Yes, but longer*".

Participants overwhelmingly preferred the tablet to the panoramic view. When asked; "*If you had to choose one technique to use with the viewshed, which would you choose?*" 24 participants chose the tablet and two chose the panoramic view. When asked, "*Did you ever forget about a technique?*" 13 of 26 participants said they forgot about the panoramic view, two forgot about the tablet view and 11 did not forget any techniques. When asked, "*Was the panoramic view still useful when given the tablet to use?*" 16 replied with "No." These responses are consistent with the dominant adoption of the bi-manual use of the viewshed and tablet, and low usage of the panoramic view.

Participants believed the tablet to be the most efficient way to get a sense of the general topography. When asked "*To best understand the overall shape of the terrain I found it best to use…*" 17 of 26 participants specified the tablet, two chose the panoramic view and seven stated they used all three techniques. Similarly, when asked; "*Was there any technique that allowed you to perform the task quicker?*" 17 participants chose the tablet while nine indicated "*No*."

IMPLICATIONS FOR DESIGN

TerraGuide is one of few multi-surface environments designed around a concrete application domain. As such, our experience in designing TerraGuide are of interest to other designers of multi-surface environments.

Where TerraGuide Succeeded and Failed

All users of TerraGuide were able to effectively use the three interaction techniques the system provides, and were able to successfully switch between the different surfaces implementing these techniques. Participants' comfort with attending to and manipulating multiple surfaces is convincingly demonstrated by the adoption of a bi-manual use of the tablet and viewshed by 23 of 25 participants (and where the other two participants used a variant on this strategy.) Participants moved fluidly and frequently between the tabletop and tablet. Rather than introducing a cognitive barrier, NASA TLX scores showed that the combined use of these two surfaces had a lower cognitive load than use of the viewshed alone.

Moreover, this combination of surfaces proved easy to learn. With only a few minutes of training, participants were able to use all aspects of the system to complete complex analysis tasks.

Our results also show that simply providing multiple surfaces supporting different interaction techniques is not a guarantee of success. Our panoramic view, as seen in study part 1, increased completion time with no commensurate decrease in error (although user confidence was increased). Study part 2 showed that given the choice, users prefer the tablet over the panorama because of its simplicity in navigation.

Over all, this indicates that systems based on optical tracking for movement and navigation like the tablet can provide significant benefit to task performance, error, and confidence, and are therefore worthy of consideration despite the complexity and cost of their implementation. Recently, optical tracking systems have become considerably less expensive, for example based on the consumer-priced Kinect camera [4].

Revisiting TerraGuide's Design Principles

We used TerraGuide to explore three design principles for systems supporting real-time spatial analysis: views should be computed in real-time, views should be tightly-coupled, and switching between surfaces should be easy. We now discuss insights from our experience with TerraGuide.

Views Should be Computed in Real-Time

One of our key technical advances over existing GIS systems is that views (particularly the viewshed and panoramic view) are computed in real-time, allowing rapid exploration of the terrain without complex dialogues or noticeable rendering times. This allowed participants to use both the viewshed and the tablet to perform *sweeping* actions over the terrain to gain a rapid overview of elevation and line-of-sight.

Thus, in addition to general streamlining of interaction, the real-time update of views enabled a new form of exploratory behaviour. Real-time updating was only possible because our viewshed computation was performed in low resolution when the viewshed was in motion. The benefit of sweeping must therefore be balanced with this lower fidelity while the sweeping is being performed.

Views Should Be Tightly-Coupled

We hypothesized that tightly coupling the views on different surfaces would simplify their use in combination. TerraGuide shows one example where this tight coupling was successful, and one where it was not.

Coupling the tablet's view to its physical position over the tabletop allows users to move between the table and tablet views rapidly, frequently, and with low cognitive overhead. The near unanimous adoption of bi-manual interaction shows that participants were able to effectively work with both views in concert. Conversely, participants struggled to interpret and use the panoramic view, whose use increased task completion time. The panoramic display was coupled with the position and orientation of the viewshed on the table, requiring users to mentally rotate the terrain to match these differing perspectives. Perhaps the panoramic view would have been more successful had it been controlled separately, rather than tightly-coupled with the viewshed.

Switching Between Views Should Be Easy

As we have discussed, participants made on average 12 switches between tablet and viewshed over their three-minute trials. This allays the fear that in multi-surface environments, users will be overwhelmed with too much choice, and with the overhead of switching between different devices. Ease of switching in this case is primarily a consequence of the tight coupling of the views, allowing users to switch between devices without loss of context, combined with the ease of holding the tablet in one hand while manipulating the viewshed in the other.

In sum, TerraGuide illustrates how these three design principles can lead to an effective use of multiple surfaces that leads to improved performance together with enthusiastic reception from users.

CONCLUSION

In this paper, we addressed problems of terrain analysis through a novel multi-surface environment consisting of three tools for terrain analysis: a real-time viewshed, a panoramic view, and a tablet-based helicopter view. The system exemplifies three design principles: views should display information in real-time, views should be tightly coupled, and switching between views should be easy.

We evaluated TerraGuide and its use as a multi-surface environment through a two-part user study. The results indicated that the tablet-based helicopter view allowed users to perform terrain analysis faster and with less error, while simultaneously lowering cognitive load and increasing confidence. The panoramic view, however, increased completion time with no improvement in error. We saw four strategies in the use of the techniques, including a near-unanimous adoption of bi-manual use of the tablet and tabletop.

Multi-surface environments are complex systems that enable powerful new interactions. Our three design principles led to the successful, effective use of multiple techniques that increased user performance. However, we discovered that simply presenting information on multiple interactive surfaces does not guarantee success.

ACKNOWLEDGEMENTS

We gratefully acknowledge the financial support of the SurfNet NSERC Strategic Network and the GRAND Network of Centres of Excellence.

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