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Applications of Interactive Topographic Maps:
Tangibility with Improved Spatial Awareness and Readability

by

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ABSTRACT

Traditional flat topographic maps are difficult to understand due to the distortion and compromise of the 3-dimensional (3D) spatial representation when it is folded into lower-dimension media (e.g. 2D). During the process, the x-y coordinate of a location can be captured but its physical elevation must be transformed using some visualization techniques, resulting in noticeable cognitive effort in comprehending the original geometric and geographic properties of the original terrain.

In this manuscript-based dissertation, I present a collection of my past publications that aim to increase the readability of topographic maps by restoring the original spatiality of the terrain - including the elevations - with a physical map representation and then superimpose additional data visualization on top of it. In this way, the entire terrain topology is kept in a scaled physical representation, allowing users to view it with natural human perceptions. Additionally, user gestures can be tracked in real-time as a sketch-based input to allow novel dynamic interaction of the map interface and data manipulation of the spatial information.

Through the chapters, I present the aforementioned concept, named *interactive topographic interface*, along with a few applications of it in different academic and industrial environments. I also report the design and results of a user study that compares the interface with traditional flat topographic maps. In the long-term, I hope that research mentioned in this dissertation inspires future interactive physical cartography to not only improve map comprehension but also facilitate better spatial and situational awareness over the map interface, resulting in an evolved map usefulness.

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To my wife, Vivien Liu

Dedicated to the loving memory of 张咪玲

1954–2011

CONTENTS

LIST OF FIGURES

If two different authors use the words "red", "hard", or "disappointed", no one doubts that they mean approximately the same thing, because these words are connected with elementary experiences in a manner which is difficult to misinterpret. But in the case of words such as "place" or "space", whose relation with psychological experience is less direct, there exists a far-reaching uncertainty of interpretation. [Jammer, 2013]

– Albert Einstein

1

INTRODUCTION

1.1 MOTIVATION

The concept of space is obscure and difficult to understand. We constantly observe and experience an in-situ three-dimensional (3D) environment, and our natural perceptions allow us to quickly grasp its basic spatial structure. However, it is hard to conceive of a space other than the one surrounding us; and attempts to do so are usually fraught with various misunderstandings and misinterpretation. Such a challenge becomes significant when a 3D space is folded in lower-dimensional media (for instance, 2D) for information storage and representation.

Representing spatial data with two-dimensional (2D) flat media has a long history. A good example is the topographic map, which visualizes the topology of terrain and represents it in a flat media such as animal skins and paper, whereas modern approaches use the screens of computers and handheld devices. Despite their popularity, traditional flat topographic maps are difficult to read for the following reasons:

1. The surface of terrain is actually a 3D spatial structure, where x-y coordinates represent the geographic position and the z-coordinate indicates the elevation. When its

3D structure is represented on a lower-dimensional media, for instance, a flat topographic map, it creates a conceptual abstraction along with possible geometric distortions, deformations, and compromises. Such an arrangement is counter-intuitive and results in the low legibility (ease of readability) of the spatial structure.

2. On traditional flat topographic maps, the elevation of the terrain at any given location is indicated by visual cues, such as contour lines or colour tinting. These visual representations share the same display area as other data visualizations on a flat topographic map and usually make the map visually overwhelming.

For these reasons, fully understanding the geometric and geographic structure topographic maps represent requires a sufficient amount of training in preparation and cognitive effort during the process. Though by carefully choosing the visualization method for specific tasks, the embedded elevation information can be easier to decode at some extend, in general traditional flat topographic map has an infamous low readability and steep learning curve.

The research goal of my PhD study, which is being reported in this thesis, is to revisit and investigate the concept of the topographic map. This includes, first, understanding the advantages and disadvantages of the current state of the topographic map, and then improving its readability with the help of new technologies.

1.2 RESEARCH QUESTIONS AND CONTRIBUTIONS

Increasing legibility is a fundamental motivation that drives map evolution. Cartographers have developed many variations on visual assistance to deliver topographic information with less cognitive investment; however, they were primarily focusing on ba-

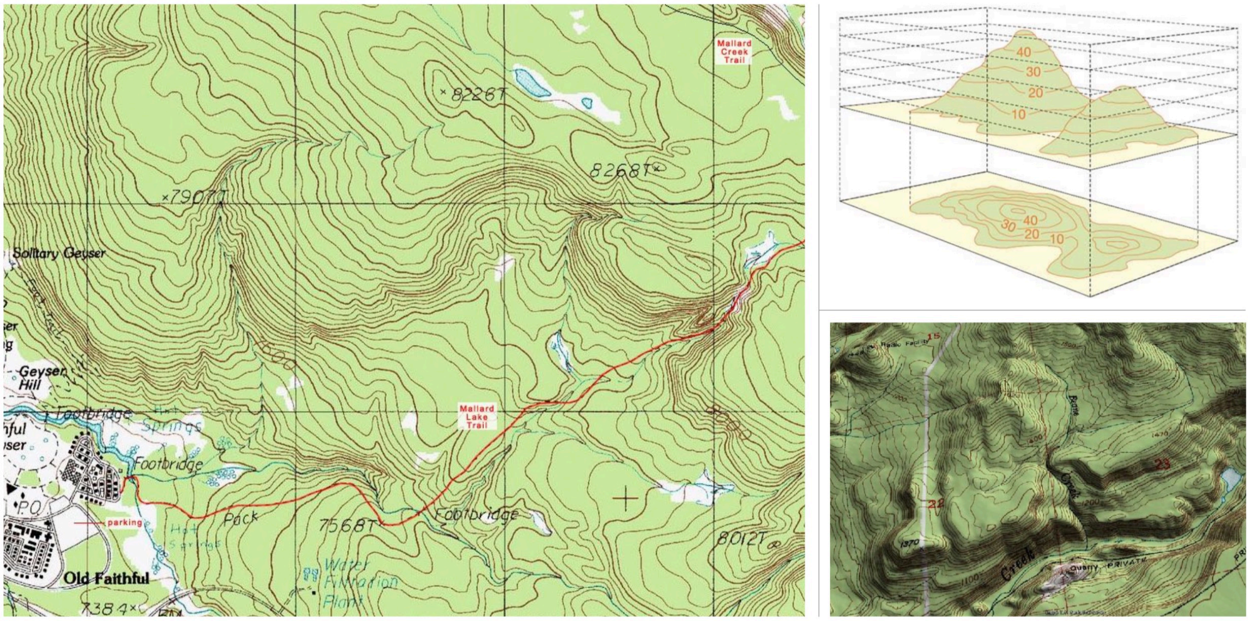


Figure 1: Examples of traditional topographic maps

sic visualization techniques (for example, drawing visual cues) and static terrain models (or sandboxes). On the other hand, a significant amount of research in the area of Human-Computer Interaction (HCI) demonstrates the power of enhancing topographic maps with immersive interfaces, but these projects use maps only to exhibit new interactive techniques rather than for the purpose of evolving cartographic readability of topographic maps.

Both the cartographic difficulties of traditional topographic maps and the current stage of HCI research lead to the following **research questions**:

1. How does tangible and immersive visualization and interaction impact the readability of the topographic map, leveraging newly developed technologies and design trends learnt from recent HCI researches, such as tangibility and sketch-based interaction? What does an evolved topographic interface look like using tangibility and sketch-based interaction?

2. What are the implications and applications of such a new topographic interface? Does it have the potential of maintaining a more intuitive spatial awareness of the topography and situational awareness of any activity that occurs in the region with less cognitive effort? Are we able to test and verify such potential in both quantitative and qualitative ways?

3. How would the new topographic interface, with the combined benefits from both tangibility and interactive visual enhancement, leverage insights from the HCI field and eventually contribute to the traditional topographic cartography? Can we increase the performance of topographic map reading tasks with this new concept and methodology?

These research questions motivated me to understand the current state-of-the-art in both Cartography and HCI, and search for a new topographic map representation that is powered by modern technologies and techniques for improved legibility of the map and spatial awareness of the map readers. In consequence, by answering these research questions, the following **research contributions** have been achieved:

1. A new interactive topographic interface (as known as the **interactive tangible topography**) that uses a) a physical map model, and b) dynamic data visualization based on user interaction in real-time. The physical representation of the map provides a scaled spatial representation of the original terrain for tangible interactions and stereoscopic perception, leveraging users' understanding of the spatial and geometric properties of the terrain without a significant cognitive load. The dynamic data visualization adds a layer on top of the physicality, rendering the topographic map with immersive experience and interaction.

Presenting data visualization in a physicalized form has recently become a trend in HCI, allowing user interactions with other sensory channels such as touch and stereoscopy on top of traditional visual cues on flat media. When applied to topographical maps, the 3D physicality does a much better job in reflecting the geometric and topographic nature of the terrain than the majority of flat map representations, due to the fact that it replicates the original terrain's shape, only on a different scale.

On the other hand, interactive digital maps (such as Google Maps) are widely used by the general public, because they are capable of rendering dynamic visual cues based on the circumstances, resulting in a less intensive and more task-oriented data interface. The interactivity also helps to increase the legibility of the map by not only optimizing contextual content dynamically (for example when to display what), but also providing the capability of active data manipulation by the user.

Note that, on the tangible map interface, the visual assistance for elevation used in traditional topographic maps (like contour lines and shading) can still be rendered over the model; however, they are completely optional since the physicality of the 3D terrain model is already sufficient to provide and maintain spatial awareness.

2. Use the aforementioned **interactive tangible topography** interface as a testbed to validate the hypothesis that the combined effort, of 3D physicality and augmented visualization, increases the legibility of the topographic maps, by providing the user solid and comprehensive spatial and situational awareness. To achieve such a goal, we revisited and redesigned classic readability task of topographic maps with the aid of recently developed HCI methodologies, and run user studies with hu-

man participants, to gain insights that can potentially bridge that connects between Computer Science and Cartography.

It has always been a very attractive motivation in the cartographic world that seeking a generic solution to improve the readability and understandability of topograph maps across the most – if not all – of the map-reading tasks. Though a great amount of effort has been dedicated to finding the perfect topographic map, map visualization techniques are still pretty much case-by-case task-based ad-hoc solutions. In other words, a particular visualization technique might be suitable for some specific tasks but fails brutally in others. And because traditional topographic maps are usually static (for instance, printed), it can become expensive when dealing complicate situations when the user needs to accomplish multiple tasks simultaneously.

This concept of the **interactive tangible topography interface**, derived from recent HCI techniques such as physicality, tangibility, and sketch-based interaction, has the potential to pave a road to an ultimate solution for topographic map readability. While it is still in its early stage, the intuitive interaction and real-time tangible and visual feedback of this interface has shown its capability of flattening the learning curve of topographic map comprehending. Also, the dynamic visual enhancement can present contextual information based on tasks, making the topographic map no longer task specific. Hence, this new topographic interface lays contribution beyond the boundary of Computer Science and extends to other areas, such as Cartography and Geoscience, where an evolved topographic map can be beneficial.

1.3 METHODOLOGY: INTERACTIVE TANGIBLE TOPOGRAPHIC MAP

The interactive tangible topographic map uses a physical 3D model to represent the terrain. Location coordinates (x- and y-values) are mapped to the surface of the model just like regular flat maps; however, the elevation (z-coordinate) is reflected with the physicality of the model so that its original geometry and topography is captured in the same scale. In other words, the distortion created by flattening the map no longer exists since the entire 3D space and all its dimensions can be preserved simultaneously, allowing users to understand the spatiality in a more perceptual and intuitive way.

Notice that, through this entire dissertation, the term “3D model” represents the physicality of the topographic map model, rather than the x-y-z spatial structure used in computer and graphics rendering.

In addition, on top of the 3D model, the interactive tangible topographic map is superimposed with dynamic visualizations using Augmented Reality (AR) techniques. It also has the ability to track user interactions so that real-time spatial data manipulation is feasible.

During my PhD study, we have designed and implemented a few prototypes of topographic map interfaces, using the same tangible infrastructure. Each project has a different visualization and interaction method employed, based on the scenario and setting of the corresponding task; however, they all share the same physicality and tangibility provided by the map model. Detailed information can be found in Chapters 2 through 5.

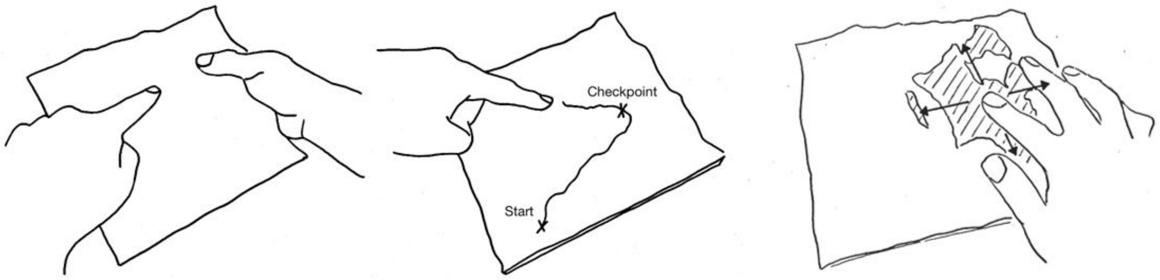
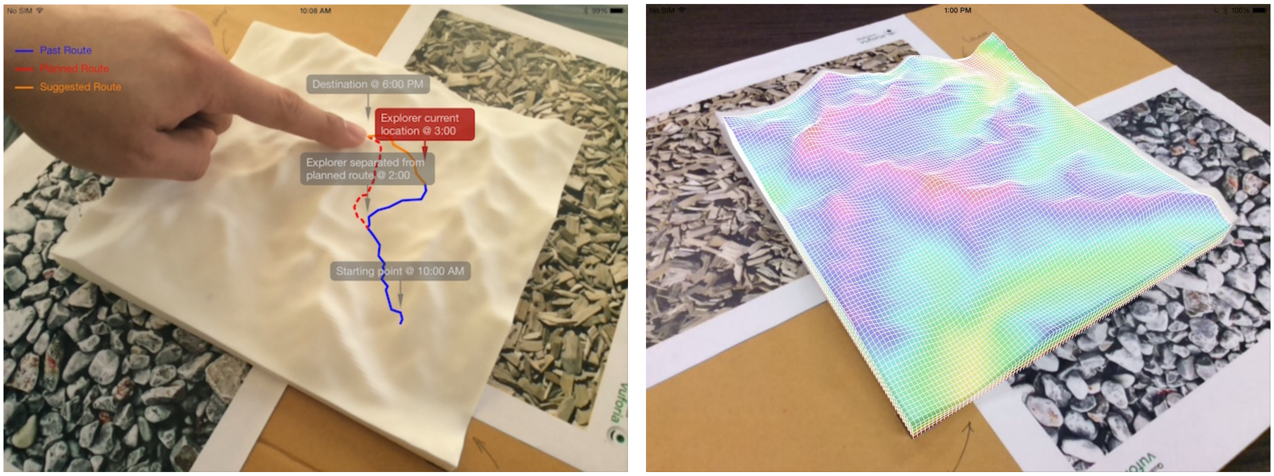


Figure 2: Design of the sketch-based interactive tangible topography interface



(a) Superimposed dynamic route and timestamps

(b) Superimposed elevation mesh

Figure 3: Prototypes of the interactive tangible topography interface in different applications

1.4 STRUCTURAL OVERVIEW

This manuscript presents five (5) papers published at various Computer Science conferences during my PhD study. They are grouped in the following three (3) themes:

(a) Observation via see-through headset

(b) Data manipulation with sketch-based gestures

Figure 4: User interactions with the interactive tangible topography interface

1.4.1 *Theme #1: Application of the interactive tangible topographic map*

This theme demonstrates some of the real-world scenarios of how the interactive tangible topographic map can be applied, including remote human collaboration and robotic tele-presentation. The goal is to enhance the spatial and situational awareness of the terrain geography and geometry by leveraging human perception and experience during field excursions and explorations, and overcome difficulties that occur particularly in large-scale outdoor environments and circumstances. This section also mentions enhancing the interface with other handheld interactions, alleviating the labour of complex gestures especially during portable usages.

This theme contains the following publications:

- Shvil: Collaborative Augmented Reality Land Navigation [Li et al., 2014]
- Flying Frustum: A Spatial Interface for Enhancing Human-UAV Awareness [Li et al., 2015a]
- Duopography[1]: Using Back-of-Device Multi-Touch Input to Manipulate Spatial Data on Mobile Tangible Interactive Topography [Li et al., 2017a]

1.4.2 *Theme #2: Understanding user interaction*

What has learnt from the project prototypes and user feedback in corresponding critique sessions motivated the pursuit of an overall understanding of the interactive tangible topographic map interface in general. We summarized common user requirements and scenarios, resulting in the design of a sequence of user studies to collect and analyze both quantitative and qualitative data while interacting with the interface. Based on the study results, we abstracted a set of design guidelines for future cartography with tangibility and dynamic interaction.

This theme contains the following publication:

- Visibility Perception and Dynamic Viewsheds for Topographic Maps and Models [Li et al., 2017b]

1.4.3 *Theme #3: Spatial awareness and immersive interaction beyond maps*

To step outside the cartographic aspect and extend the idea into higher dimensional abstraction, a project was developed allowing users to explore the counter-intuitive 4D

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[1] Duopography = duo + topography

geometric shapes with superimposed visual cues and interactions. This is an experiment of generalizing potential benefits of spatial representation in a conceptual fashion, even in higher dimensions, using perceptual and immersive visualization and interaction.

This theme contains the following publications:

- And He Built a Crooked Camera: A Mobile Visualization Tool to View Four-Dimentional Geometric Objects [Li et al., 2015b]

While papers in Theme #1 and Theme #2 are strongly related to both research contributions, this paper in #3 has a remote connection with the mean topic. Therefore Theme #3 is located in the appendices of this dissertation.

Note that only publications that I first-authored were included, meaning I completed the majority of - if not all - the design, writing, and the implementation of the prototypes. Other papers in which I participated as the second or third author were intentionally excluded so that this manuscript-based dissertation is focused on the academic contribution during my PhD study.

1.5 THE USAGE OF THE PHYSICAL MAP MODEL

The physical 3D topographic map used by the aforementioned prototypes and projects has the dimensions of 20cm-by-20cm-by-3cm. This map model was 3D-printed from hard plastic to prevent it from any geometrical deformations during direct user interactions. The map model is completely white so that coloured visualization superimposed on the surface of the model can be preserved without colour distortions, as if it is printed on a piece of white paper. The texture of the model surface is basically smooth with a little noticeable roughness, which is similar to touching a wooden surface. This chose of the material provides a certain level of grip when applying hand gestures upon the model surface, rendering the map model into a touchscreen with an irregular interactive surface.

One thing worth mentioning is that, in the applications of remote collaborations (Theme #1), the physical map model was principally used in the **conceptual** way, meaning the scaled map does not always represent its original terrain. When it was necessary for the map model to represent the outdoor environment, we carefully chose regions on the topographic map and the outdoor environment, so that they both shared similar geometric features (such as hills and valleys). In this way, the outdoor user, whether a human explorer in *Shvil* and *Duopography* or via a robotic entity such as the one in *Flying Frustum*, could easily connect and overlay the surrounding with the scaled tangible map interface at where the activity was happening, even though they were actually operating on the same map model in different projects.

The reason that the same 3D map model was necessary to be reused across multiple prototypes was due to legal reasons or missing topographic data of some area. For instance, it is illegal to fly drones over provincial lands in Alberta, Canada so we had to test the *Flying Frustum* prototype in a private property, of which it is not feasible to create a 3D topographic model. It was also because middle size 3D printing was relatively expensive at the moment when most of the papers were published, therefore creating and then printing a 3D map model for each single project was not practically feasible.

Fortunately, since our system is designed to exhibit the interaction novelty rather than numerical measurements, the conceptual usages of the physical map model were sufficient to convey the user in map reading tasks, regarding the geometry and topography of the original terrain, without noticeable misconceptions. Moreover, under the circumstance when only the map model was used as an abstract data interface, such as

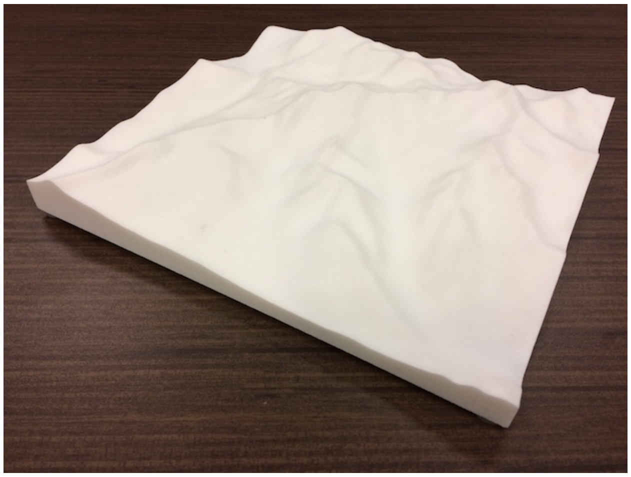

Figure 5: The physical 3D terrain model used in the interactive tangible topography interface

the map study mentioned in Theme #2, the entire working environment must be conceptual. In this case, the physical topography map needs to look realistic but not necessary to represent any real terrain in our universe.

In addition, due to the map size and texture, such a selection of the physical map model in facto has limitation and only reflects some of the aspects of the tangible topographic map usage. I will elaborate on this in the section Limitations of the chapter Conclusion.

1.6 ON THE USE OF THE PRONOUN 'WE'

The research projects described in this dissertation were collaborations. Although I conducted the majority of the design and implementation of in all papers presented as chapters of this manuscript-based dissertation, I have received noticeable help from collaborations in shaping the project concepts, data analysis, and proofreading of the writing. For the aforementioned reason the pronoun 'we' will be used throughout the dissertation to collectively refer to these contributors and myself.

Part I

THEME #1: APPLICATION OF THE INTERACTIVE TANGIBLE TOPOGRAPHIC MAP

2

SHVIL: COLLABORATIVE AUGMENTED REALITY LAND NAVIGATION

2.1 PREFACE OF THEME I (*shvil*, *flying frustum*, AND *duopography*)

This theme contains a collection of my previous publications that attempted to validate the concept of the tangible topographic map interface with real-world applications that involve topographic map reading. During the process, three (3) projects were designed and prototyped, each applied the novel interface in a different field excursion and exploration scenario, where the productivity was limited primarily by the low legibility of traditional flat topographic maps.

The journal started from tackling the difficulty in remote collaboration between indoor overseers and outdoor in-field explorer, in which maintaining and synchronizing a sufficient amount of spatial and situational awareness among all participants was a challenge. The outcome was the project *Shvil* [Li et al., 2014], which provided both indoor and outdoor users with an augmented reality (AR) enhanced communication channel of shared spatial data and activities.

The next step was replacing the outdoor explorers with remote-controlled robotic entities. The goal was to test whether the tangible topographic map interface could offer not only the remote spatial and situational awareness to the user, but also a decent telepresentation of the robotic entity. The consequential project, *Flying Frustum* [Li et al., 2015a], was designed and implemented in the setting of a drone, which can be indirectly controlled by sketch-based gestures, using the physical map model.

Preliminary user interviews in these projects showed promising results. Participants liked the concept of tangible topographic map interface and agreed that it made the topographic map easier to read, resulting in a better comprehend of the space that the map represented. Nevertheless, an inconvenience in the interaction with the physical 3D map model was discovered due to the rough and irregular model surface, rendering unexpected challenges in completing the hand- or sketch-based gestures over the physical model. This finding motivated me to design the third application of the interface, named *Duopography* [Li et al., 2017a], which had a back-of-device touch-surface mounted at the back of the 3D model to increase the user-friendliness of the interface with providing the basic gestures on flat touchscreens that users were already familiar with (such as pan, zoom, etc.).

All three (3) projects attempted to increase the map legibility with the concept of the tangible topographic map interface, using different real-world applications, with successes. All together the positive results not only validated the idea qualitatively, but also gave me the motivation of further studying the potential of the new interface quantitively via a formal user study (see Theme #2).

2.2 INTRODUCTION

Collaboratively planning and executing route finding, land navigation, and exploration tasks can be time-consuming and exhausting both physically and mentally, even when the topological terrain is known. Collaborative land navigation tasks are common in many domains including archaeology, geology, reservoir engineering, petroleum engineering, military operations, and mountaineering.

Shvil (Hebrew for path or trail) attempts to address tasks where a remote overseer (indoor user) and an in-situ explorer (outdoor user) are performing land navigations collaboratively. *Shvil* also attempts to provide better situational awareness [Endsley, 1995] and task awareness to overseer and explorer by allowing both of them to experience the task representation physically through a tangible medium, as well as visually via AR techniques.

Shvil is designed to enrich the experience of both explorer and overseer and improve the efficiency of their collaboration by grounding it in the physical and spatial aspects of the task. The design of our system (shown in Figure 6) simulates the scenario where an offsite overseer is provided with a 3D physical printout of the terrain and with interactive AR visualizations showing the task status superimposed on the terrain model. At the same time, the in-the-field explorer is provided with interactive AR visualizations superimposed on the terrain in-situ.

Beyond the immediate scope of computer supported cooperative work (CSCW) that *Shvil*, with its mixed reality augmentation, affords, we see value in using the 3D printout of the terrain as a physical representation of topographical data. The physical printout can become a rich interactive medium, capable of providing tangible modality and feedback in addition to the abstract, scaled-down representation of the environment, which the traditional map provides.

Here we present our current prototype of *Shvil*, critique our design and outline our future plans for this project.

Figure 6: A simulated design overview of *Shvil*, the collaborative system

2.3 DESIGNING SHVIL

We now use the country itself as its own map, and I assure you it does nearly as well.

– Lewis Carroll's Sylvie and Bruno, 1893

Shvil aspires to convey the spatiality of the area being navigated into an interactive medium. For the overseer, this spatiality is embedded in the physical 3D printout, and for the explorer, the spatiality is expressed via the actual physical terrain that becomes an active, one-to-one-scale map (Figure 6).

The component of *Shvil* used by the overseer handles the data visualization technique in an offsite (indoor) facility, while the explorer component deals with the data visualization in the field. In addition, each component also takes care of the presentation of the shared data, which allows *Shvil* to facilitate the collaboration between the explorer and the overseer. Both the overseer and explorer components of *Shvil* use AR to enhance the interactive environment and to access the 3D spatial navigational data in real-time. The explorer interacts with the physical terrain using AR directly in the field; however, the overseer benefits from accessing the 3D printout of the terrain, not only as a realistic illusion enhanced by the superimposed AR visualization, but also the tangible provides additional perceptional advantage and understanding of the terrain as experienced by the explorer.

Shvil is based on a 3D printout model of the terrain data (Figure 7). With the current advances and accessibility of 3D printing technology, such printouts are easy to generate and becoming less costly. We expect that, similar to how conventional 2D maps are commonly printed and distributed, 3D printouts of terrains could be easily produced and distributed in the near future.

Shvil's overseer interface combines the 3D printout with AR tracking (see the bottom left image of Figure 6). The route information is rendered via mobile devices running the AR library with the virtual representations overlaid and correctly aligned on the physical 3D printout. When changing content in the virtual image, the overseer sees these changes instantly applied upon the physical 3D printout. The experience is enhanced when the overseer moves around the physical model, since the AR device automatically detects the location and orientation of the model in real-time and adjusts the virtual image along with it. Various routes and related points of interest from the explorer are rendered in the AR environment in real time. Since the virtual image presented to the overseer is aligned with the physical model, it feels like those routes and points of interest are marked on the physical presentation of the terrain directly (see left half of 6).

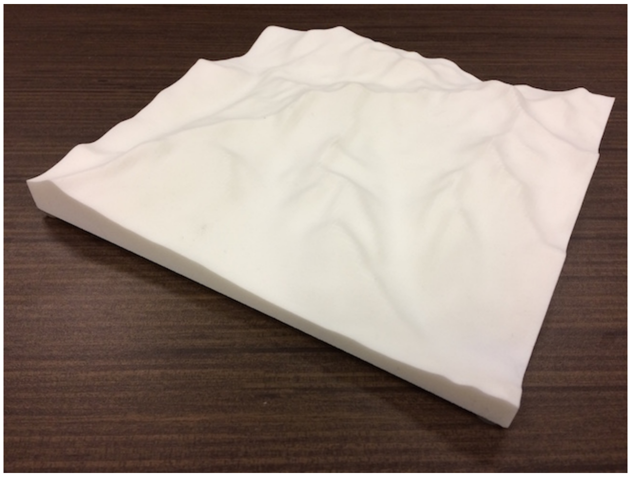

Figure 7: The physical 3D terrain model used in *Shvil*

The explorer component of the system is used as an aid for an in-the-field explorer to identify the routes and various points of interest on the terrain. It is essentially a geo-location based AR system that helps to identify aforementioned information in the scene, based on the explorer's location and direction. The system overlays this information onto the live camera feed in order to create the in-situ experience. The explorer interface demonstrates an egocentric system, while the overseer component presents an exocentric view of the terrain (see right half of Figure 6).

Since the goal of this system is to facilitate the collaboration between the overseer and the explorer in real-time, both people in different locations are de facto examining the same set of data. However, rather than a birds-eye view as experienced by the overseer, the explorer observes the information in-situ. Also, information will be updated dynamically to either part of the system simultaneously.

Augment reality (AR) has been frequently used in many areas, including civil engineering and design [Ghadirian and Bishop, 2008] [Schall et al., 2008] and topographical terrain exploration [Lapides et al., 2012]. Several past applications proposed using AR to support collaborations between experts and remote field users [Poelman et al., 2012] [Kurata et al., 2005].

Moreover, AR has also been applied in coordinating terrain navigation between an indoor user and the outdoor user [Höllerer et al., 1999] [Leibe et al., 2000], with gestures and physical props [Stafford et al., 2006]. However, as far as we know *Shvil* is the first to use a 3D printout of the terrain as the interactive medium representing the topographical data in a physical form in such collaborative task, and is unique in providing a combined experience of both visual (AR) and tangible (3D printout) contextual feedback within the collaborative task.

With respect to the tracking applications, there are many commercial applications such as "Apple Find My Friends"[1] and "Google Location History"[2] that superimpose locations on traditional 2D maps. However, rather than 2D maps, here we are more interested in visualizing 3D land navigation, thereby facilitating remote collaboration between the overseer and the explorer.

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[1] https://www.apple.com/apps/find-myfriends/

[2] https://maps.google.com/locationhistory/

2.5 IMPLEMENTATION

Shvil is designed with loose coupling as a goal, so any component may be changed without impacting other parts of the system. There is an intermediate server to handle the information sharing, and standard REST APIs are used for data transmission in between. We implemented both the overseer and explorer parts on entirely different devices (iPad Air vs. Lenovo tablet) and coding environments (iOS vs. Microsoft Windows). The explorer component was implemented on Lenovo ThinkPad Tablet and Windows environment while the overseer component was developed on iPad Air and iOS.

In the overseer interface, the AR and the 3D printout of the terrain are used for creating the exocentric visual experience. Markers are placed around the 3D printout, and Qualcomm Vuforia[3] is used as the image recognition library for obtaining the location and orientation of these markers. Based on the spatial information, the mobile device adjusts the virtual image correspondingly when the viewer walks around the physical model. Navigational information, including the route of the field explorer and other points of interest, are visually mapped onto the physical model to give the impression that they are indicated and labeled on the model directly (see the bottom left image of Figure 6).

In the explorer component, a Windows tablet is used as the portal device for the AR visualization. Location and orientation of the explorer are collected from the built-in GPS sensor, compass, and inclinometer. Based on this data, routes and points of interest are mapped to the physical position so that it looks like they are painted "on the ground" from the explorer's perspective (see the bottom right image of Figure 6).

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[3] `http://www.qualcomm.com/solutions/augmented-reality/`

Note that due to the difficulty of obtaining the digital geographic data of the area where we tested our system, the 3D terrain model used in the prototype is not the exact but a decent substitute for the topographic map, which closely simulates the features of the original terrain it represents (hills, valleys, etc.). We believe the physical model is sufficient for providing the overseer with enough spatial awareness and understanding of the represented area, which creates no difficulties in conveying the concept of *Shvil* the collaboration system. Other than the 3D model, the rest of the system, including dynamic data visualization and remote data communication, is fully functional and performing in real-time during the test of the system (shown in the screenshots of Figure 6).

2.6 CRITIQUE AND LIMITATIONS

Currently, *Shvil* is a proof-of-concept prototype. We are still developing and improving the accuracy of the GPS and compass readings, communication latency between the overseer and the remote explorer, and low routemapping resolution.

Besides the aforementioned technical limitations, we are also aware of limitations related to our design approach. Our augmented reality mediators are based on consumer-level tablets. This results in the users, especially the explorer, needing to interact with relatively inconvenient and heavy handheld devices. This design approach could be improved dramatically by moving *Shvil* onto head-mounted or wearable devices, such as Google Glasses, that would likely provide a more natural experience.

On the other hand, our topographical terrain 3D printout required considerable resources, and certainly there exist approaches that use other tangible mechanisms to represent the terrain [Ishii et al., 2004] [Leithinger and Ishii, 2010]. However, with the progression of 3D printing technology driving down the cost, and with more precise 3D printers becoming abundant, this barrier could be reduced if not completely eliminated.

In addition, we would like to print a real 3D topographic map model using the actual geographic data of the testing area, rather than a closely simulated terrain model.

2.7 FUTURE WORK

We would like to extend the *Shvil* concept to multiple (non-collocated) explorers, and also to multiple (noncollocated) overseers, all relating to the same geographical location by either walking on top of it physically or by interacting with copies of its 3D printed representation. Another improvement to *Shvil* we are planning is to incorporate more sophisticated interaction techniques, such as using touch directly on the 3D model in the case of the overseer, and gestures in the case of the explorer.

We are exploring the possibility of applying *Shvil* to domains where the topography of the physical site could be augmented with metadata well beyond *Shvil*'s current basic terrain surface navigation. For example, we are planning to use *Shvil* for collaborative exploration of interactive visualizations of oil and gas reservoirs, where enabling collaboration between remote overseer experts and in-situ explorers can be very useful to track and explore complex domain specific features.

2.8 CONCLUSION

In this paper we presented a collaborative land navigation system, named *Shvil*, which uses AR and 3D printing technologies to facilitate and visualize route planning and execution. This system allows two collaborators, an in-situ explorer and a remote overseer, to exchange route information during a field exploration using the terrain as the interactive medium. Although *Shvil* is a design concept with only a proof-of-concept prototype implementation, future directions and improvements were discussed.

3

FLYING FRUSTUM: A SPATIAL INTERFACE FOR ENHANCING HUMAN-UAV AWARENESS

3.1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are increasingly ubiquitous and have many well established uses, including various reconnaissance applications in search-and-rescue and military settings [Goodrich and Schultz, 2007] [Mitchell et al., 2005]. There are also many other applications emerging, from cinematography[1] to shipping and delivery[2].

Challenges of controlling these UAVs remain however. Many aspects of UAV control could benefit from further development, from more efficient interaction with low-level flying mechanisms, to higher-level issues of teleoperation and control [Goodrich and Schultz, 2007] [Mitchell et al., 2005]. *Flying Frustum* focuses on the high-level issues of teleoperation when interacting with UAVs which are performing a reconnaissance task over a terrain. *Flying Frustum* provides the UAV operator with a 3D printout of the terrain, which can be used to plan and draw flight paths for the UAVs. A visualization of the UAV's position on the 3D terrain is superimposed on the 3D printed model and a

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[1] https://www.lily.camera/

[2] https://www.amazon.com/b?node=8037720011/

Figure 8: Illustration of the concept: *Flying Frustum* allows users to teleoperate an UAV with sketch-based gestures on a physical terrain model and steams the UAV's view frustum

correctly situated frustum can display real-time information about the UAV. In the case of this prototype the information displayed is a video feed from the UAV's camera. *Flying Frustum* is designed to provide a remote operator an enhanced level of human-UAV awareness [Drury et al., 2006b] [Drury and Scott, 2008] and improved situational awareness [Endsley and Garland, 2000] when controlling one or more semi-autonomous UAVs. Our approach closely follows the footsteps of Drury, et al. [Drury et al., 2006a] which argues that situated streaming information from a UAV would increase the operator's situational awareness. However, *Flying Frustum* extends this paradigm by using a 3D terrain printout with augmented reality visualizations as the interactive medium.

In this paper we present a prototype realizing the *Flying Frustum* concept, based on visualization superimposed on a 3D printout using either a handheld or headset augmented reality interface, and a Parrot Bebop drone as the UAV. While our current prototype is still preliminary, it does allow us to reflect on the strength and weaknesses of the *Flying Frustum* approach, argue the benefits of providing streaming information from the UAVs correctly situated and superimposed on their current 3D location, and to outline our future plans regarding this interface.

Maintaining situational awareness has a crucial impact on the design of remote teleoperation interfaces [Endsley and Garland, 2000] [Nielsen et al., 2007]. While situational awareness theory originated from aircraft control, air traffic control and other critical interaction settings, it soon emerged as a more general CSCW concept, which could be applied to various workplace scenarios [Gutwin and Greenberg, 2002]. The field of Human-Robot Interaction (HRI) adapted situational awareness onto its own unique collaborative settings and tasks, using the term HRI Awareness, and recognizing the inherently different and asymmetrical roles humans and robots play within the HRI collaborative settings [Yanco and Drury, 2004] [Drury et al., 2003]. Work was also done on applying HRI awareness to UAVs in related settings and tasks, for example by studying Desert Hawk UAVs and their operators [Drury et al., 2006b]. These efforts resulted in a discussion of a subset of HRI-awareness called Human-UAV awareness [Drury and Scott, 2008], which is specifically concerned with the interaction between UAVs and their remote operators.

Our work follows closely on this path, and can be seen as a direct extension of the aforementioned previous work [Drury et al., 2006a] where a UAV video stream was superimposed onto a geo-referenced 2D map of the terrain and was shown to improve the operators' situational awareness. *Flying Frustum* builds on these works by extending the interface into 3D using a physical printout of the terrain, a pen-based interface that is used to draw the commands on the terrain, and 3D situated streaming video from the UAV. Our work makes use of existing augmented reality interfaces (handheld and headset-based) in keeping with the extensive use of augmented reality in CSCW as seen in works such as [Li et al., 2014] [Billinghurst and Kato, 2002] [Höllerer et al., 1999] [Stafford et al., 2006] [Kurata et al., 2005].

3.3 DESIGNING *flying frustum*

The original motivation for our design came from control difficulties and interface limitations discovered in real-world scenarios during geo-science and petroleum field explorations. Such an excursion may require one or possibly multiple UAVs to efficiently cover geological features that are difficult or even impossible to reach, such as cliffs and canyons. In other cases UAVs may provide a more cost effective and less labor intensive alternative to manned aircraft when collecting data over a piece of terrain such as done by SkyHunter[3]. In both scenarios users have basic knowledge of the terrain that is to be explored, however the challenge is to rapidly deploy and effectively teleoperate the UAV while maintaining a high degree of overall situational awareness and human-UAV awareness simultaneously.

Our design goal when creating *Flying Frustum* was to develop a situated 3D interaction with a UAV. The foundation for our spatial interface design is the 3D interactive medium, which is based on a scaled down model of the terrain that the UAVs are exploring. We create this medium using 3D printing, generating a physical representation of the terrain. The 3D printout provides users with a tangible entity that accurately and intuitively communicates detailed topographic information through both visual and tangible sensation. Augmented reality is used to superimpose spatial information onto the physical printout (Figure 9).

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[3] `http://www.skyhunter.ca/`

(a) Using a 3D printout model as a physical representation to the topographical terrain (b) Augmented reality visualization is superimposed onto the model

Figure 9: *Flying Frustum*'s physical representation to the topographical terrain and superimposed AR visualization

We designed the augmented reality layer of *Flying Frustum* considering both see-through AR headset (using Epson Moverio) and handheld AR screen (using iPad Air) (Figure 10). The 3D terrain printout is used as the interactive medium for sending user commands to the UAV by sketching on the terrain model, and for communicating information back to the user via 3D situated visualizations superimposed on the terrain. In order to correctly situate the various 3D information components, *Flying Frustum* needs to track the position and orientation of the handheld or the headset interface relatively to the 3D printout, and the position and orientation of the 3D sketching stylus.

We designed a set of pen-based interactions performed directly on the physical model of the terrain that allow the operator to control the movement of the UAV. We used physical pen-based interactions to address the "fat finger" problem and to enhance the precision of the operator commands to the UAV, while still allowing direct, tangible interaction and intuitive understanding of the topography of the 3D printout and therefore the terrain (Figure 11).

(a) handheld screen (b) see-through headset

Figure 10: *Flying Frustum*'s augmented reality devices

Similar to drawing a path on a traditional map, the operator may define a path for the UAV by sketching a line upon the surface of the physical model.

After the operator has created a path, the drone will fly to the location that is marked the start point of the path on the model, and then move along the path until it reaches the end point. The visualization of the UAV flight on the model corresponds spatially and temporally to the actual flight path of the drone in the real world.

Once the UAV starts following the path the operator traced on the 3D model, it is designed to stream live video footage from its camera and displays it on the far plane of a view frustum which is situated on the physical model according to the location and orientation of UAV on the actual terrain. The view frustum constantly adjusts its position and orientation to mirror the real-time activities of the actual UAV in the field (Figure 12). This design is based on the paradigm that situated streaming information would enhance the human-UAV awareness and situational awareness by helping the operator

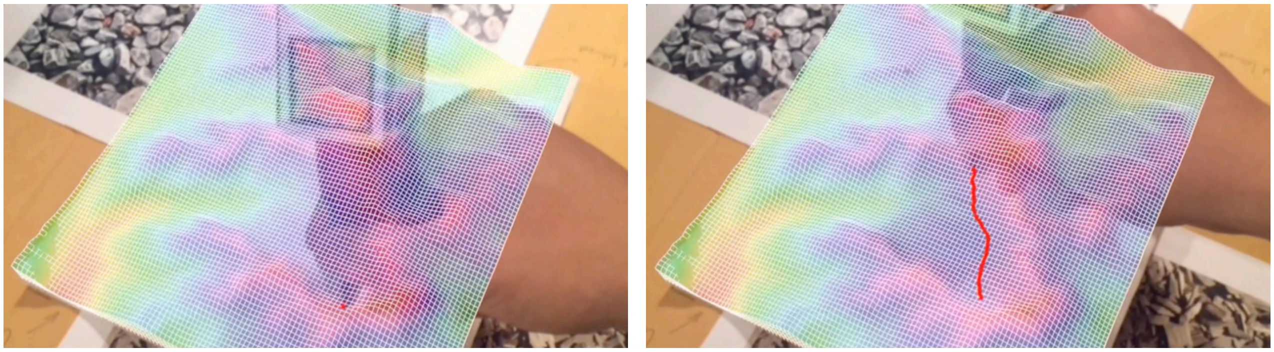

Figure 11: *Flying Frustum*'s pen-based interaction for sketching the flight path of the drone

understand exactly where the drone is and what it is doing at the same time, with the streaming video correctly situated on top of the 3D physical terrain. This builds upon work demonstrating similar ideas in 2D non-AR settings [Drury et al., 2006a].

With a certain level of automation [Parasuraman et al., 2000], we expect *Flying Frustum* to further release the operator from constant observation of the drone's activities, which is common in traditional linear controlling of UAVs. Our design assumes that the UAV is semi-autonomous, meaning that it is able to hover and follow a predetermined path without human supervision until receiving any further instructions.

We believe that such an interface can help the operator maintain a high level of situational awareness without dramatically increasing the workload or cognitive load, which in turn could enable the operator to control multiple drones simultaneously.

3.4 IMPLEMENTATION

The prototype of *Flying Frustum* presented in this short paper is a preliminary proof-of-concept. The 3D printed interactive medium including the augmented reality functionality, the pen input and the 3D video frustum are fully realized and are completely

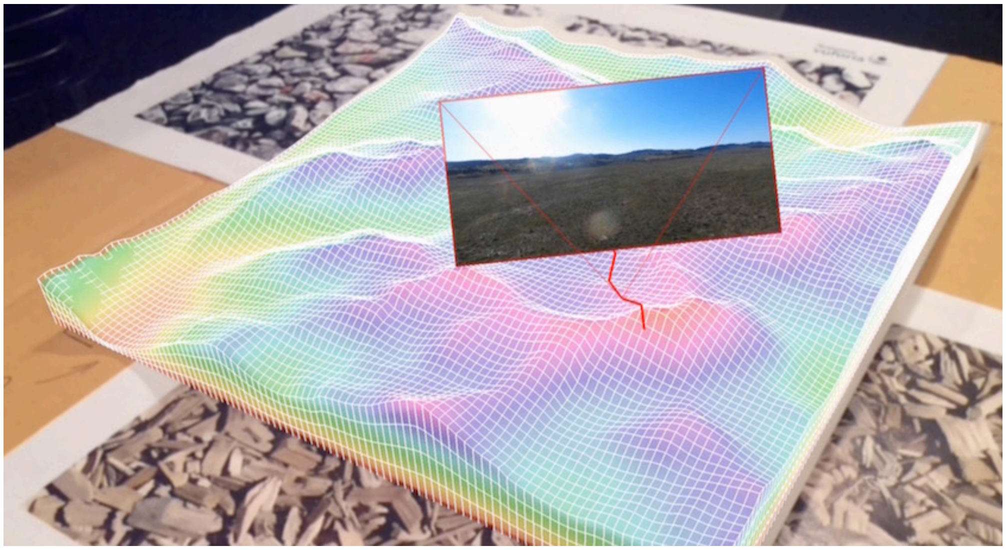

Figure 12: Illustration of how video footage captured by the drone can be displayed on the view frustum in the augmented reality visualization

functional. However, direct control and communication with the UAV has not been implemented and we use the Wizard-of-Oz prototyping method when flying the UAV and when playing the video back to the user via the situated frustum.

Our prototype was tested with both an Epson Moverio[4] headset and an iPad as the augmented reality devices, and the Qualcomm Vuforia[5] engine was used to illustrate the visualization. The 3D printout is made from strong flexible plastic[6] and was acquired from a commercial 3D printing company (Shapeways Inc.). We use the iPad as our primary augmented reality device to realize our proof-of-concept.

A Parrot Bebop Drone[7] is used as our UAV. It is a lightweight drone capable of performing 3-axes movements, and recording full HD video footage.

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[4] http://www.epson.jp/products/moverio/

[5] https://developer.vuforia.com/

[6] http://www.shapeways.com/materials/strong-and-flexible-plastic/

[7] http://www.parrot.com/ca/products/bebop-drone

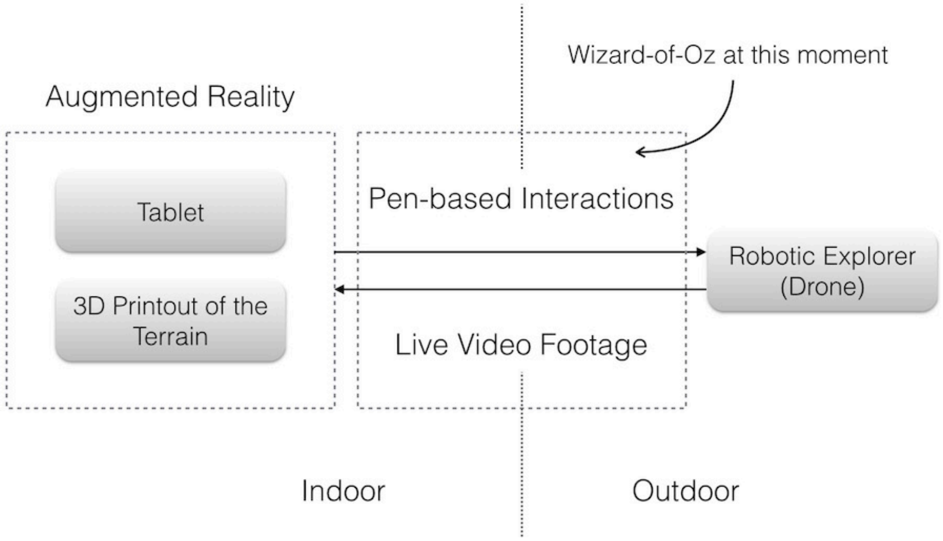

Figure 13: *Flying Frustum*'s structure of the implementation

Due to the lack of reliable network coverage by commercial cellular networks and ISPs at certain locations the drone was operated, the communications between the operator and the UAV is implemented by means of the Wizard-of-Oz technique, including sending the instruction and receiving the video footage (Figure 13). During the test of the system, we pre-defined the route of the drone and used the pen-based interface to draw the path on the 3D physical terrain model accordingly. Then we flew the drone in the field following the planned route. The drone captured the video footage during the flight and the footage was later sent back and rendered on the superimposed frustum. We argue that, since we were testing the feasibility of the interface rather than the remote data communication, such a Wizard-of-Oz prototype still allows us to reflect on the overall validity of the *Flying Frustum* concept.

Also, drone flying is restricted in many public areas of Canada, so we ended up testing the system in a private property, rendering it impossible to obtain the geographic data of the terrain. However, we carefully selected the testing area so that, even though the 3D physical model is not the actual topographic map of the area, it closely simulates the geographic feature of the terrain (hills, valleys, etc.).

3.5 LIMITATION AND FUTURE WORK

Although we see *Flying Frustum* as a direct extension of past work that demonstrated that situated streaming information improves human-UAV awareness [Drury et al., 2006a], our augmented reality approach still requires formal evaluation and validation, and the preliminary prototype we presented here still needs to be solidified to make sure it is ready for use in an actual user study. One limitation is the current state of augmented reality technology, and specifically the questionable usability of see-through headsets primarily due to the limited field of view. However, we believe that with the rapid development of this technology future augmented reality headsets will have much larger field-of-view and higher fidelity. We are looking forward to integrating future headsets (e.g. Microsoft HoloLens) in *Flying Frustum* as well as to exploring other visual augmentation approaches such as projection mapping on top of the 3D model.

We would like *Flying Frustum* to support a much richer gesture vocabulary. For example, allowing the operator to sketch a loop to indicate an area on the 3D printout, or to use a pre-defined search pattern (e.g. spiral or grid), which will direct the UAV to continuously monitor a path above the terrain, to search a specific area, or to follow a specific flight pattern. Such an extended gesture vocabulary could have applications and benefits to various tasks such as search and rescue operations.

In addition, we plan to study how *Flying Frustum* can improve the operator-UAV ratio, and allow control of a several UAVs simultaneously. We are interested in learning the overall workload and performance impact of *Flying Frustum* on operators of multiple

UAVs, especially in comparison to other UAVs control mechanisms (e.g. [Mitchell et al., 2005]).

3.6 CONCLUSION

We presented a new human-UAV interface we call *Flying Frustum*, which facilitates spatial situated remote interaction with drones. *Flying Frustum* uses a 3D printout of the terrain as an interactive medium. The UAV operator can use pen-based interactions to input flight paths and send commands to the UAVs by sketching directly on the physical topographical model of the terrain. The UAVs can in turn present information such as streaming video back to the operator via the augmented reality overlay on the terrain model. The information is situated in a 3D view frustum on the model in the correct location corresponding to the UAV's current position. We outlined our design approach using handheld and headset augmented reality techniques, and our current preliminary prototype based on a Parrot Bebop drone.

Though our work on *Flying Frustum* is still ongoing and while we have not performed a formal evaluation, we believe that *Flying Frustum* provides a unique human-UAV interface, and that the 3D real-time situated interaction it affords is intuitive and increases human-UAV awareness over previous works.

4

DUOPOGRAPHY: USING BACK-OF-DEVICE MULTI-TOUCH INPUT TO MANIPULATE SPATIAL DATA ON MOBILE TANGIBLE INTERACTIVE TOPOGRAPHY

4.1 INTRODUCTION AND MOTIVATION

We present the design of *Duopography*[1] (Figure 14), a dual-surface mobile tangible interface for spatial representation and manipulation of topographic information.

Classic topographic maps demonstrate the consequences of representing 3D spatial information in lower-dimensional media [Harvey, 1980]. A terrain topography is a 3D spatial structure, featuring geometric and topologic properties such as elevation. When being represented on a flat media like a traditional 2D topographic map, original 3D spatial information of the terrain needs to be abstracted, distorted, and compromised. Considerable effort in physical and tangible interaction was dedicated to finding ways to preserve and visualize the topography in its original 3D form as much as possible, lowing users' cognitive load and enhancing their spatial awareness when interacting with the topography and interpreting the embedded spatiality (such as the following

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[1] Duopography = duo + topography

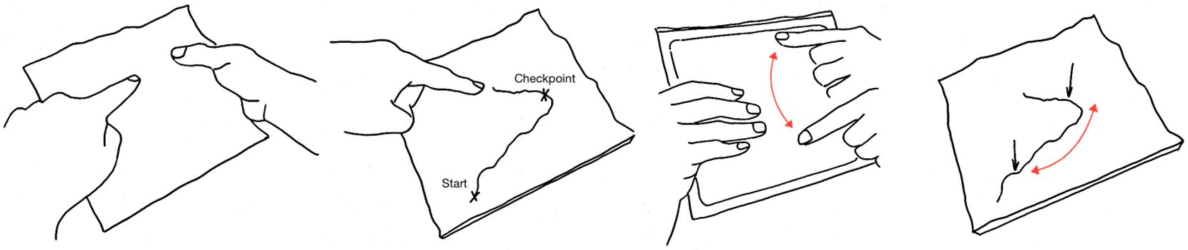

Figure 14: *Duopography* is a dual-surface mobile tangible interface for spatial representation and manipulation of topography

papers [Ishii et al., 2004] [Leithinger and Ishii, 2010] [Piper et al., 2002] [Willett et al., 2015]).

Past work on improving topography abstraction focused on the provision of either physical embodiments or stereoscopic vision [Mair, 2011] [Rase, 2011]. In addition to representing the terrain with a scaled 3D model, physical topographic maps are often superimposed with rich visual augmentations and supported with touch interactions, which allows users to sense the corresponding fluctuation of the terrain [Tateosian et al., 2010]. Combining both tangibility and visualization in these new topographic representations increases the readability of the map contents compared to flat topographic maps. Ideally, these new representations provide better spatial awareness of the original topography, leading to a presumed less steep learning curve and a reduced cognitive load when reflecting on the represented space.

However, 3D physical topographic representations create new interactive challenges when it comes to direct interactions with the irregular terrain surface [Roudaut et al., 2011]. Specifically, sketching on the irregular surface of the terrain model can be difficult, since the movement of the operating pointing device (finger or stylus) can be interrupted by the constantly varying friction and geometric shape of the local area, creating a suboptimal user experience. Following, high-level interactions with the topography that world have been easy to perform on a flat interface could become difficult on the 3D physical one. For example, when planning a field excursion route on the topographic model, the user may experience difficulties when physically tracing and scrolling along the spatial twisted and entangled route path with a fingertip on the bumpy surface of the physical terrain model.

Duopography addresses this challenge by providing on its 3D front an interactive irregular surface that physically and visually representing the terrain topography, while its flat back simultaneously supports back-of-device gestures that are hard to perform on the irregular front. In the following sections we present the design, current prototype, and early evaluation of *Duopography*.

4.2 RELATED WORK

There has been a long history of making physical topographic maps in cartography, serving purposes from leisure modeling to stereoscopic data visualization, though most of them are stationary models [Mair, 2011] [Rase, 2011]. Also, there are many recent contributions that transformed the classic topographic maps using novel interaction techniques, some provide enriched interaction with dynamic animation (for example, Relief Shearing [Willett et al., 2015], Flying Frustum, and the HERE location intelligence installment[2]), while others are capable of shape-shifting, active or passive, allowing user to sculpt the physical topography with various input methods (like Illuminating Clay [Piper et al., 2002] [Ishii et al., 2004], Relief [Leithinger and Ishii, 2010], TanGeoMS [Tateosian et al., 2010], etc.).

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[2] `http://360.here.com/2015/09/30/this-3d-model-changes-how-we-visualize-location-intelligence/`

Duopography is also strongly influenced by previous work on back-of-device input. A back-of-device touch surface may facilitate authentication [De Luca et al., 2013], extends the operating area [Baudisch and Chu, 2009], or be integrated with the front screen in order to create a see-through effect for data and virtual object manipulation (such as Lucid Touch [Wigdor et al., 2007] and a similar double-side input device [Shen et al., 2009]) and grasping (PinchPad [Wolf et al., 2012]). Studies on gesture input with back-of-device surfaces demonstrated that users were, in general, sufficiently dexterous in using selected fingers on both sides of the device for various tasks [Löchtefeld et al., 2013] [Wobbrock et al., 2008].

There exists strong research effort in either direction of (1) physically and visually enhanced topography, and (2) back-of-device interaction; however, it is very little explored that how to use both techniques together. Our motivation came from the willingness to improve the notoriously challenging touch interaction on the tangible topographic surface, during which the user is constantly interrupted by physical and visual occlusion caused by the irregular geometry. We therefore contribute the concept of introducing the back-of-device interface as an expanded operation area, resulting in more intuitive and fluent interaction and better physical and visual exposure of the physical topography itself.

4.3 DESIGNING DUOPOGRAPHY

The design goal of *Duopography* is to provide a mobile device that incorporate both a tangible interactive topographic map representation and a back-of-device interface. It targets at users who need to maintain spatial and situational awareness of the topography while performing out-door activities in real terrain. We hope its physicality and the

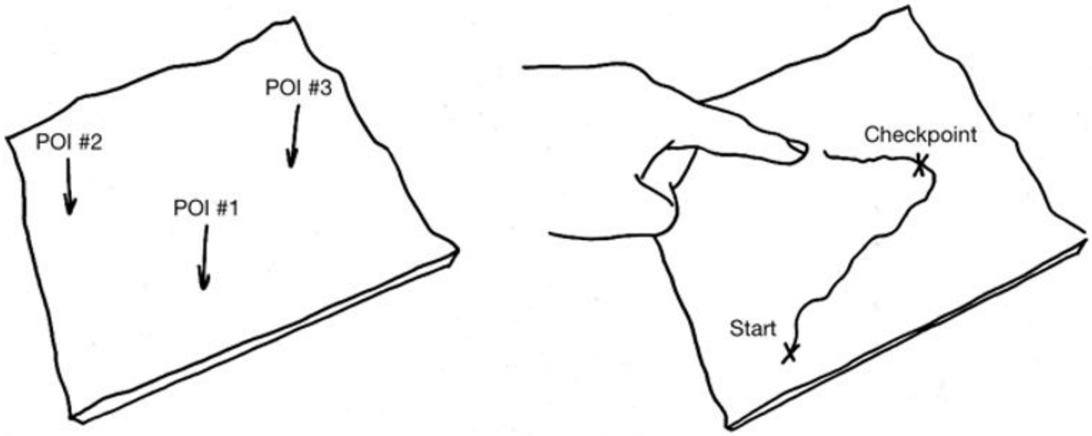

Figure 15: *Duopography* allows users to sketch on a visual-argumented 3D physical terrain model

regular touch-interaction experience provide obvious affordance for understanding the topography, resulting in cognitive eases.

The design of *Duopography* is centered around its physical topographic terrain model. The surface of the model, which represents a region of the terrain in a scaled form, supports multi-touch capability and is visually augmented. Following, the irregular topographic surface of the model not only allows the tangible feedback reflecting the geometric structure and geographic features of the terrain, but also serves as a canvas for direct sketching with fingertips. Dynamic visualization of topographic and geoscience data is superimposed on the physical surface of the model, providing a similar experience to a regular touch screen, though *Duopography* replaces the screen with the irregular 3D physical topography on its front.

We also choose the physical terrain model with a comparable size and weight to the form factor of a tablet-size mobile device, allowing it to be picked up, held, and played with. Such a setup mimics the experience of manipulating nearby objects by hand, resulting in stereoscopic visual cues, direct and indirect rotation, etc., along with touch screen interactions that most of people are familiar with.

The front surface of *Duopography* allows the user to input new or to modify existing spatial data by sketching in the scaled 3D space (Figure 15). However, unlike drawing on a flat and smooth 2D plane, sketching on an irregular surface can be difficult, requiring extra effort and uncomfortable gestures to achieve [Roudaut et al., 2011].

Duopography uses a back-of-device input area as a solution to this problem, with the goal of integrating the familiarity of interaction with ubiquitous flat screens into the irregular 3D topographic front surface. A flat multi-touch surface is mounted on the back of the physical terrain model, facing backwards, supporting pinching, tapping, panning, and other multi-touch gestures (Figure 14, and also see Figure 19 for its implementation). The back-of-device interface, which remains invisible during interactions, does not replace the functions of the front terrain surface. Instead, it offers an operation area for additional manipulation, adjustments, and fine tuning on the front-facing spatial data that would have been difficult to direct interact using gestures sketching on the irregular front surface.

Previous work shows that absolute inputs are significantly difficult to perform on a back-of-device surface, especially when the hand behind is not visible [Yang et al., 2009]. Hence, our design is based on using the back-of-device surface to support only relative positioning rather than absolute positioning, which is left exclusively to the interactions with the front of *Duopography*.

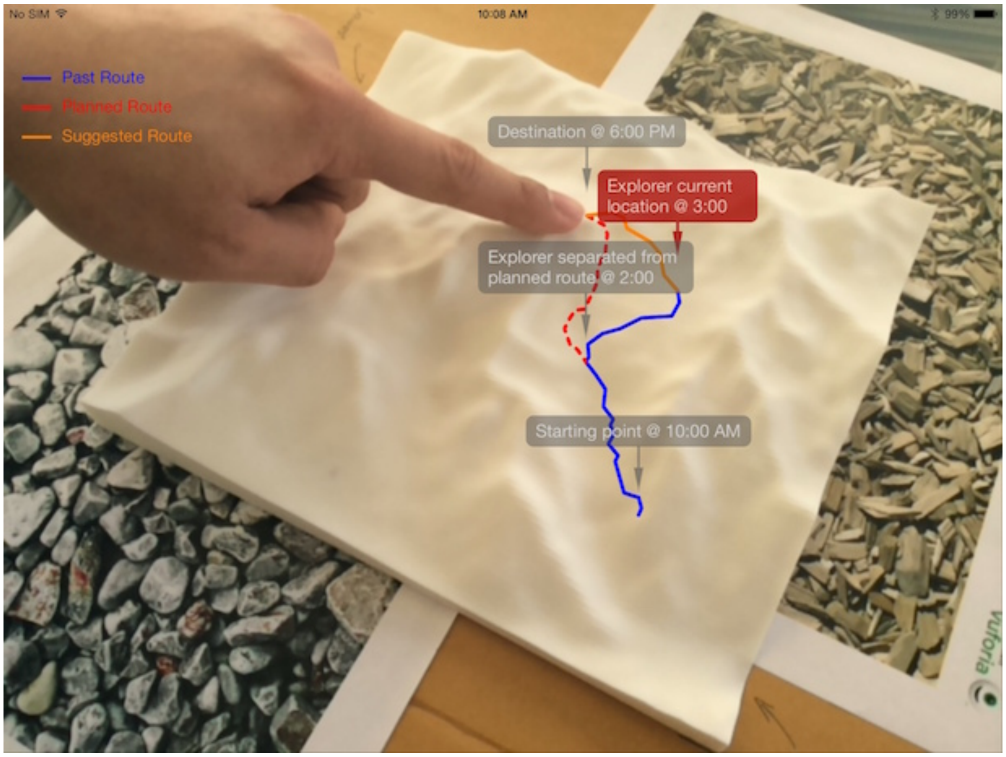

Figure 16: Illustration of *Duopography*'s superimposed AR visualization over the 3D printout topographic model, viewing via a tablet screen

4.4 IMPLEMENTATION

Our current *Duopography* prototype is still preliminary but was capable of demonstrating the possibility and feasibility of our mobile tangible topography vision.

The physical terrain model is a 3D printout made from hard plastic, due to the lightweight and durability of the material (Figure 16). The model has a dimension of roughly 20 cm by 20 cm by 5 cm, which is similar to the size of a regular tablet. These physical properties, including the size, weight, and the material, are designed to encourage users to treat it as a typical handheld mobile device without much physical or cognitive effort.

It is worth mentioning that, during the test runs of the system, the 3D physical model did not represent the actual terrain, due to the lack of sufficient geographic data. However, there is a diagonal valley across the physical terrain model (see the photo of the model in Figure 16) and we found a valley in the Banff National Park (Alberta, Canada) that shares very similar geometric features, and used the area as the testing environment in the preliminary survey (reported in the evaluation section) to validate the feasibility of the system.

Visualization is superimposed with using augmented reality (AR) (Figure 16). The edges of the terrain model are extended with cardboard to place AR markers around. An AR device, either a see-through headset (Epson BT-200) or handheld display (iPad Air), detects the location and orientation of the AR markers with its built-in camera (Figure 17 & 18). Spatial coordinates of the markers are then captured in real-time, and the visual image is rendered accordingly and overlaid on the live camera footage. As a result, both the visual image and the live footage are shown on the screen of the AR device synchronously. The Vuforia AR SDK was used to handle marker tracking and rendering in our current implementation.

Touch input on the front of *Duopography* is supported by a Leap Motion attached on the AR device, tracking the movement of users' fingertips (Figure 17 & 18). The dynamic AR image, combined with finger tracking, creates the illusion that the irregular surface of the physical model is capable of capturing user sketching and display situated visualization directly on the physical 3D front-facing surface of *Duopography*.

The back-of-device touch surface was realized using a back-facing iPad Air mounted behind the 3D physical terrain model (Figure 19), providing a flat and smooth interactive surface, unlike the irregular and fluctuate front one.

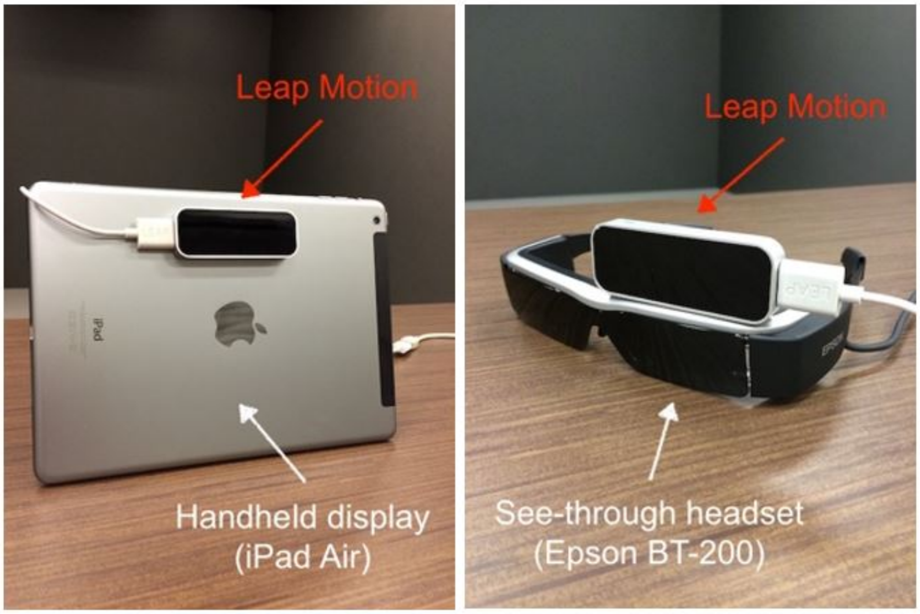

Figure 17: *Duopography* uses a Leap Motion is attached on the AR device to capture sketching over the topographic terrain surface

Though both faces of the terrain model are touch surfaces that are capable of receive gesture inputs, they serve distinguishable purposes due to their difference in geometric shapes. As mentioned previously, users may use sketch on the topographic surface for creating or modifying spatial information, while the back-of-device surface is used for performing multi-touch gestures that are not suitable for the irregular front face. Since the back-of-device surface along with the operating hand are not visible, we eliminated absolute positioning tasks that requires high precision from *Duopography*'s back surface. We also decided against using transparent or pseudo-transparent screens, exposing the rear hand and its movement [Wigdor et al., 2007] [Shen et al., 2009], as we were concerned that the transparency of the terrain model may introduce additional visual distortions on the top of the already somewhat overwhelming topography.

While we tested both a see-through headset (Epson BT-200) and a handheld device (a second iPad Air that is different from the back-of-device one) for realizing the AR, it

Figure 18: Use *Duopography* with wearing the see-through headset in field

(a) Sketching on the front irregular topography surface to create spatial data

(b) Interacting with the back-of-device flat surface for manipulating exiting spatial data

Figure 19: Demo of operating *Duopography* on both interactive surfaces; not at the actual site

is clear that, as the AR display, handheld device will render *Duopography* impractical to use with only two hands. We include the handheld AR approach as the screenshots (in Figure 16, 19, etc.) we use were generated from the iPad and benefited from the much larger field-of-view of the device.

4.5 INTERACTING WITH DUOPOGRAPHY

We demonstrate a usage scenario of *Duopography* (Figure 19). To plan a route during a field excursion using the mobile *Duopography*, the user first sketches it on the topographic surface. The tangibility provided by the terrain surface plays an important role, since the geographic and topographic feature along the route will have significant impact on the performance of the excursion. Once a route is planned, the user can use the back-of-device surface to scroll along the route by panning, and select a checkpoint to review detailed information such as the tentative arrival time at that particular point. During the process neither the terrain model nor the dynamic spatial data is occluded because the operation surface now is behind the physical model. (Figure 20)

The user then pinch-to-zoom on a part of the route to observe a higher resolution view of the area nearby a specific point. During this process, denser checkpoints may appear depending on the zoom level, and while zooming the scale of the visualization may be different than that of the physical model. When the user releases the fingers from the back-of-device device, the overlaid visualization shrinks back elastically. (Figure 21)

Notice that the zoom feature allows the user to dynamic modify the scale of the superimposed visual overlay, creating an inconsistency with the terrain representation. We included it in the design due to both the lack of material flexibility of the map model (i.e. the map model cannot be zoomed physically), and users' willingness of checking out

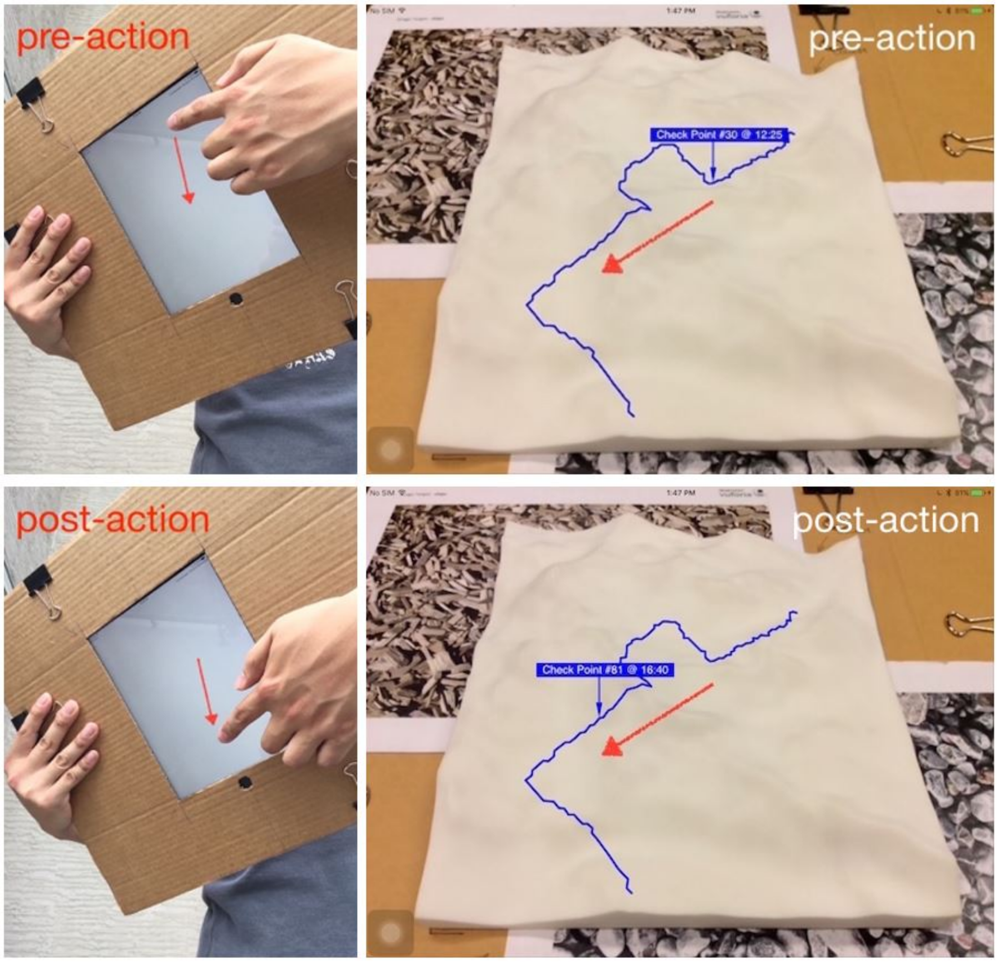

Figure 20: Interaction method of *Duopography*: panning on the back-of-device surface to scroll along the route at different checkpoints

detailed information around a certain region on the terrain. Certainly, it will be replaced with more appropriate approaches such as a shape-shifting surface so the physical map representation can be zoomed along with its visual cue.

In addition, during our critique sessions with participants we observed the usages of the pinch-to-zoom feature with little confusion. We argue this is still a valid operation because the zooming action only takes place in a relatively short period. In the process the participants were still able to keep their spatial memory of the physical model, even though during the action the visual presentation is mismatched with the physical one.

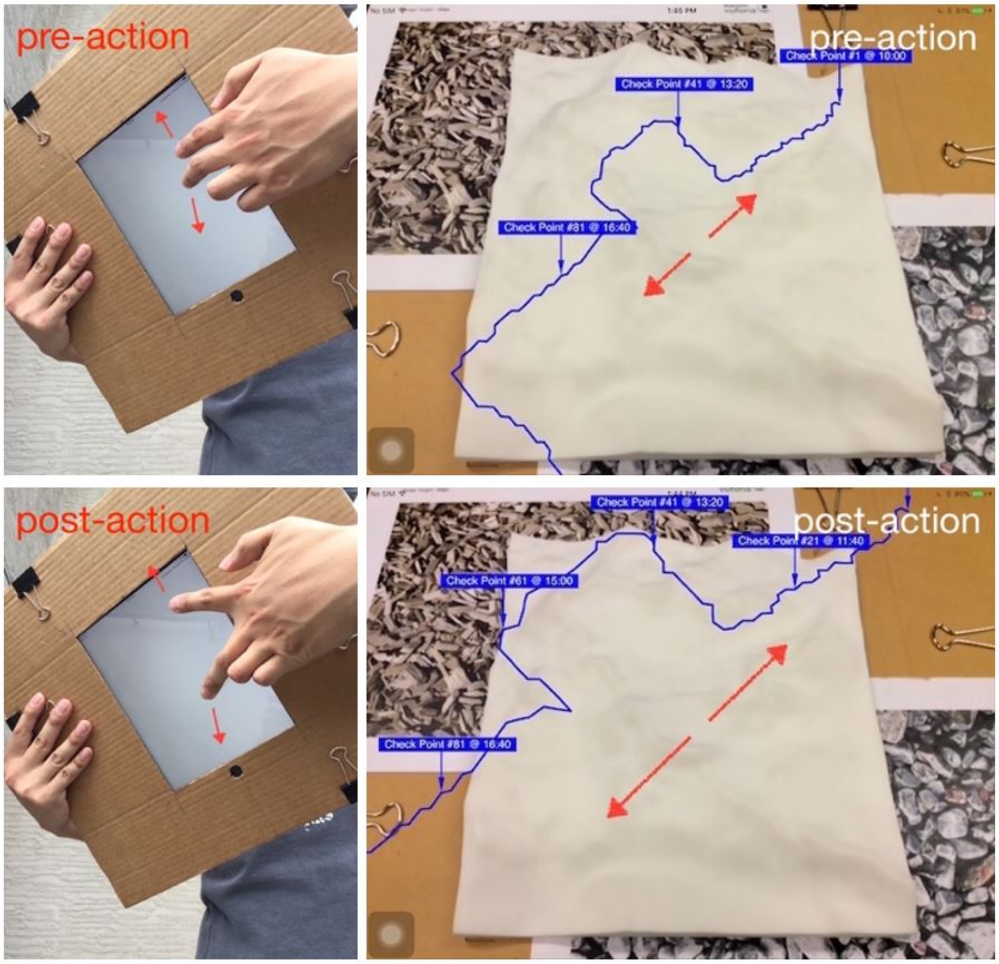

Figure 21: Interaction method of *Duopography*: pinch zooming a local region on the back-of-device surface for a temporary glance of the detailed info at different zoom scales

4.6 PRELIMINARY EVALUATION

We conducted an early evaluation of *Duopography* while hiking in Banff National Park, AB, Canada. The reflections we collected below are very preliminary in nature and are based on our current early prototype. At this stage, we focused on qualitative results via observations and questionnaires, and the main purpose was to provide some validation to the design approach. More formal quantitative precise confirmation of our interaction technique is clearly required and is beyond the scope of this paper.

As mentioned before, the physical model used during the evaluation was not the actual topographic map of the area. However, it shares certain terrain features with the area, enough to convey the spatial knowledge of the environment to the participants, who were fully aware of the simulation of the physical topographic map. We argue that, due to the fact that the goal was to examine the concept of the interactive interface, the test was still valid as long as the map representation is not counterintuitive.

Our preliminary evaluation included 7 participants who used *Duopography* in limited interactive scenarios. Among our participants 3 were males and 4 females; 2 were familiar with topographic maps and 5 not. The input was collected during multiple hiking sessions.

In the early phase of the study participants were asked to attempt absolute positioning on the back-of-device. Unsurprisingly [Yang et al., 2009], we observed the difficulty of absolute positioning due to the invisibility of the rear hand. Participants constantly tilted the device in order to expose the rear hand, and in some extreme cases the topographic model was even flipped over completely. This finding matches the result of previous research efforts and led to us eliminating absolute positioning in *Duopography*'s back-of-device interaction techniques.

We also noticed that, during using the 3D printout model as the topographic map, slopes and curvatures on the model had significantly impacts on the performance and accuracy when sketching on model surface. Participants often needed to adjust their finger positions, sometimes repeatedly, in order to reach certain part of the terrain model, causing noticeable cognitive efforts. This is consistent with the finding in previous research on curved surface interaction [Roudaut et al., 2011], and further supports *Duopography*'s back-of-device operations.

Generally, all the participants understood and managed to use *Duopography*'s dual-surface topography interface, along with the concept of the back-of-device touch surface. Most of the participants suggested that the back-of-device surface can be beneficial over the classic flat topographic map, increasing spatial awareness and cognitive ease during map reading. However, participants also highlighted some of *Duopography*'s limitations. Most of the complains focused on the less accurate and occasionally unresponsive tracking method, along with the current prototype's oversized AR marker (roughly 60 cm by 50 cm as shown in Figure 16, 19, 20, & 21) and relatively heavy weight (the glasses weigh 88g; 212g combined with the controller[3]).

4.7 CONCLUSION AND FUTURE WORK

Our *Duopography* prototype is still very preliminary, and the early study we conducted is limited. Aspects of the interface, such as the map, were tested in a conceptual way. Also, both the fidelity of the prototype and the scope of the study need to be improved prior to any conclusive and specific confirmation of *Duopography*'s interaction techniques.

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[3] `http://www.epson.jp/products/moverio/bt200/feature/`

Technical improvements would include the replacement of the current *Duopography* prototype components with cutting edge ones, such as integrating the Microsoft Hololens in the front-facing display in order to determine how the dynamic visualization experience can be enriched. We also plan to experiment with a larger coverage of input gestures and with more complex spatial data, ideally taken from a valid application domain such as orienteering or geoscience. In addition, we also intend to engage with geoscience domain experts in order to add a more domain-specific and valid interactive layer to *Duopography*.

In this short paper we presented the design of *Duopography*, a dual-surface mobile tangible interface that has a front 3D irregular topographic interface for sketching spatial data, and a back-of-device flat multi-touch surface for inputting gestures that more suitable for flat touch areas. We contribute a prototype and the results of a preliminary evaluation of a dual-surface topography interface combining 3D printed front and a flat back-of-device. We foresee a future for *Duopography*-like maps which would allow rich in-the-field direct interaction with mobile 3D physical topography, with a back-of-device layer enabling interaction techniques that are hard to perform on the font-facing irregular surface.

Part II

THEME #2: UNDERSTANDING USER INTERACTION

5

VISIBILITY PERCEPTION AND DYNAMIC VIEWSHEDS FOR TOPOGRAPHIC MAPS AND MODELS

5.1 PREFACE

In this chapter we want to in theory understand whether the interactive tangible topographic map interface can be recognized more intuitive, and if so, then is it possible to quantify the benefits it brings. To answer these questions, we conducted a user study [Li et al., 2017b] with 20 participants to collect quantitative and qualitative data of topographic map interactions. More specific, we compare the results of traditional visibility tasks performed on traditional flat topographic maps vs. interactive tangible topographic interface rendering dynamic viewsheds as visual aids. In this chapter we report the design of the study and conclude the advantages in intuition and experience if the interactive tangible topographic map is used. Based on the study results, we also suggest a design guideline for any future topographic cartography with using interactive tangibility. The contents of the following sections are from the original publication but reorganized to fit in the structure of the dissertation.

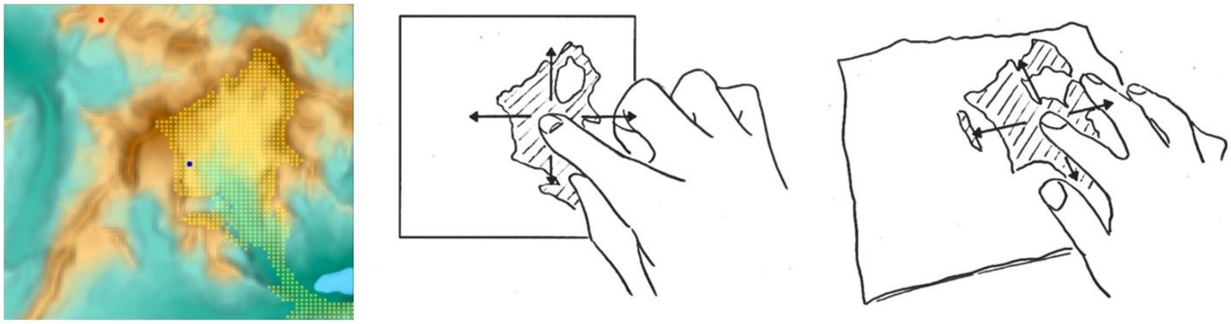


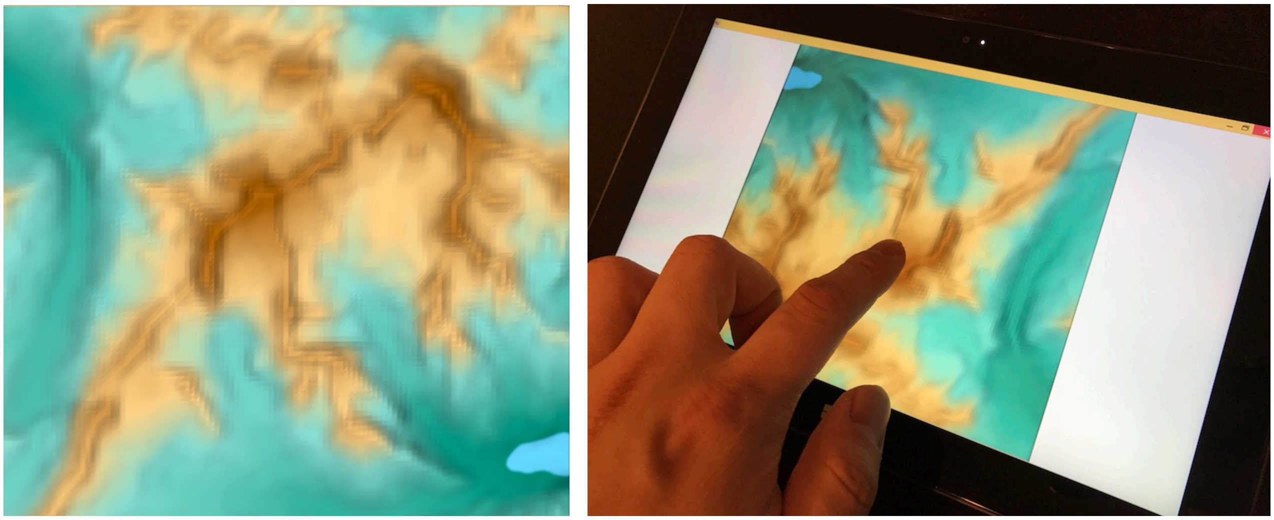
Figure 22: The study explores the impact of dynamic viewsheds that provide real-time interactive feedback about terrain visibility on both 2D touch-screens and 3D tangible terrain models

5.2 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 [Harvey, 1980] [Schofield and Kirby, 1994]. 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 [Willett et al., 2015], which animates terrain in order to provide additional depth cues, can



(a) The 2D layer tinting map

(b) Areas in brown have higher elevation and areas in green are lower

Figure 23: 2D layer tinting map used in the study

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 [Piper et al., 2002], Relief [Leithinger and Ishii, 2010], TanGeoMS [Tateosian et al., 2010], 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 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.

5.3 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 [Haeberling, 2002]. 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 [Buchroithner, 2012].

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 [Petrasova et al., 2015]. Digitally-augmented models and 2.5D shape displays, such as the MIT media lab's Illuminating Clay [Piper et al., 2002], Relief [Leithinger and Ishii, 2010], and SandScape [Ishii et al., 2004], and Nokia's experimental HERE installation[1] 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

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[1] http://360.here.com/2015/09/30/this-3d-model-changes-how-we-visualize-location-intelligence/

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 [Phillips et al., 1975] [Phillips, 1982].

Recently, work on interactive 2D maps has shown that novel interaction techniques like interactive "relief shearing" [Willett et al., 2015] and viewshed manipulation [Oskamp et al., 2015] 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 [Wilson, 2002] for 3D terrain models, and discuss a variety of ways in which the physical and spatial characteristics of terrain models [Jansen et al., 2013] [Sharlin et al., 2004] create opportunities for tangible interpretation and interaction [Ullmer and Ishii, 2000].

5.4 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.

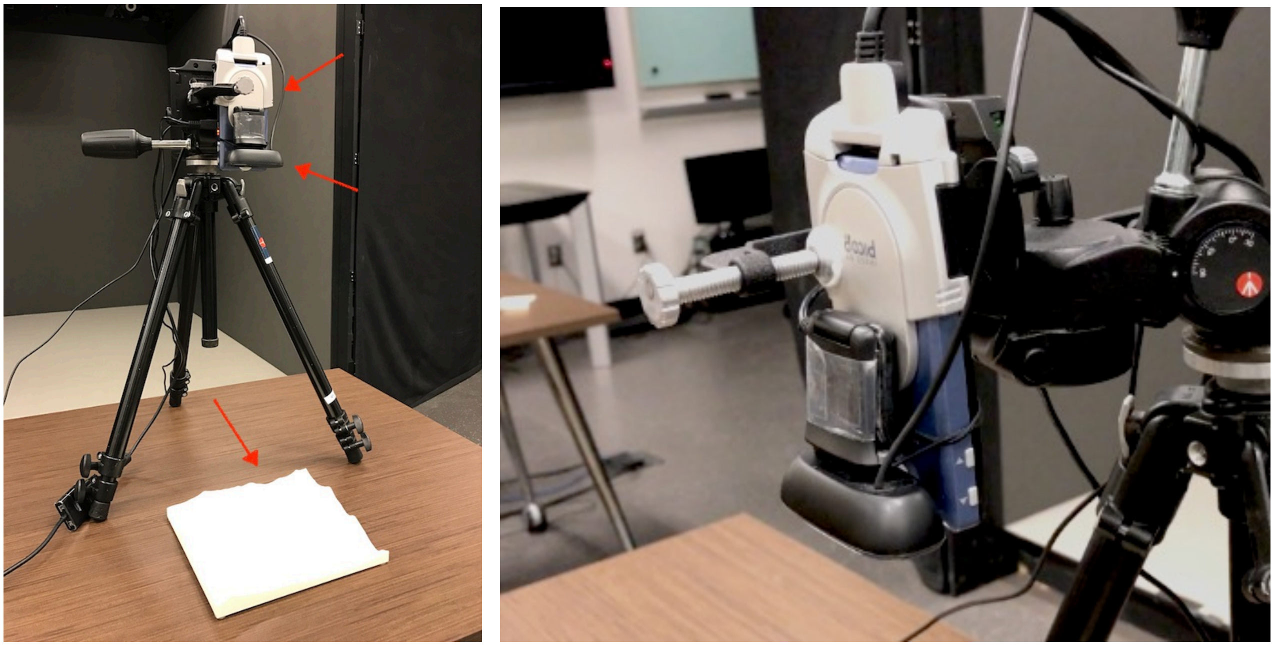
5.4.1 *2D Topographic Maps*

As a baseline, we created a simple topographic map (Figure 23) which encodes elevation information using a combination of relief shading and layer tinting. Because prior research by Phillips and others [Phillips et al., 1975] [Phillips, 1982] 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 [Patterson and Jenny, 2011]. Specifically, we used a set of continuously progressing tints similar to those favored by Imhof [Imhof, 2015], 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 x 13 cm on a Microsoft Surface 3 tablet, whose touchscreen is capable of capturing user interactions on the map.

5.4.2 *3D Terrain Models*

We also created an 18 x 18 cm 3D printed terrain model of the same region out of white plastic (Figure 24). To provide interactive input and output, we augmented the model with a camera and pico-projector mounted roughly 40 cm above the surface of



(a) Our 3D tangible map captures user gestures with a webcam

(b) And uses a pico-projector to overlay imagery on the physical terrain model

Figure 24: Study setup: webcam and pico-projector in detail

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 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 [Couture et al., 2008] and TanGeoMS [Tateosian et al., 2010].

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 x 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.

5.4.3 *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 [Tandy, 1967] 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[2] and CARTO[3], 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. 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

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[2] https://www.arcgis.com/features/

[3] https://carto.com/

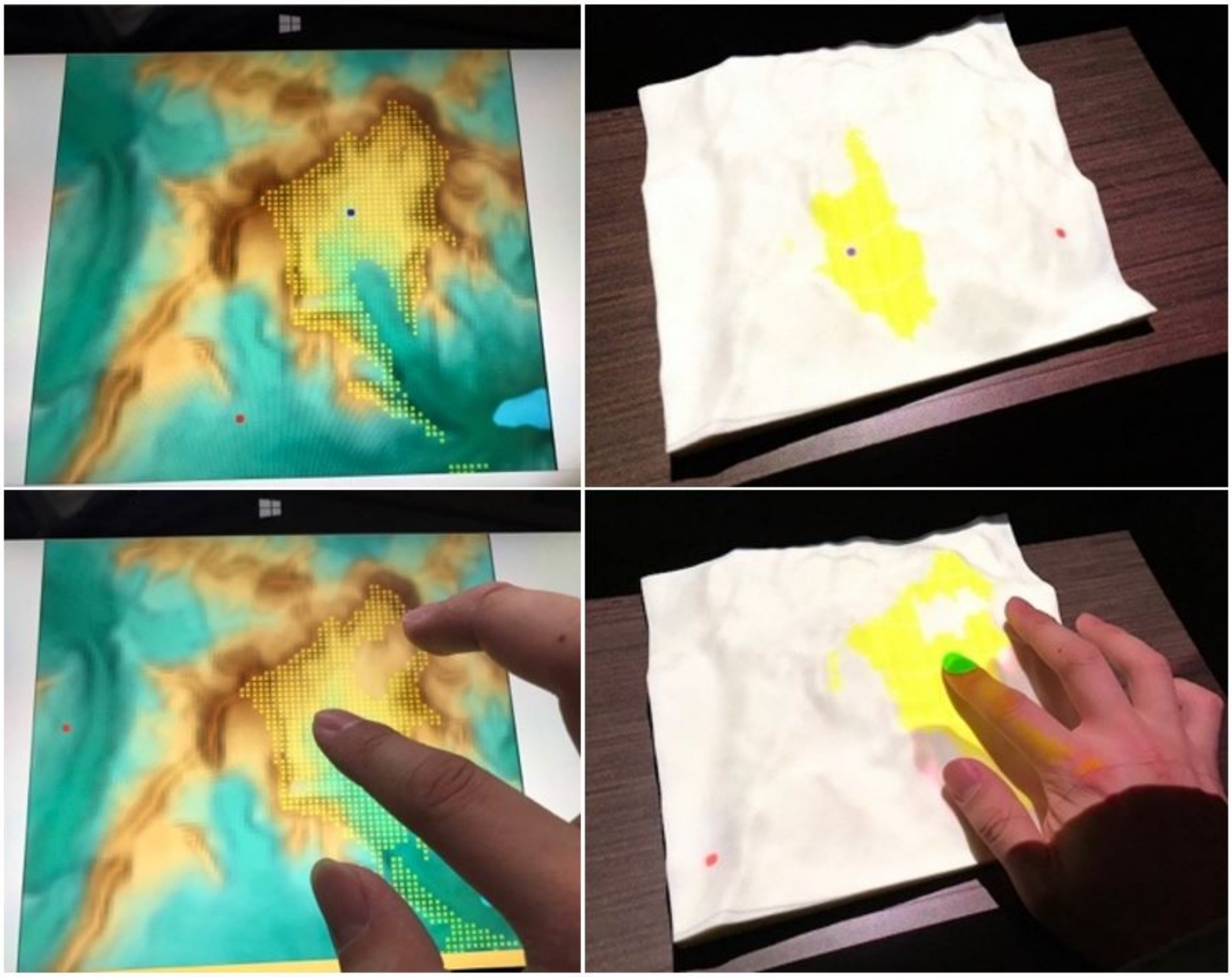


Figure 25: Dynamic viewsheds rendered on the 2D map and the 3D map can be manipulated in real-time using touch interactions

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 25).

5.5 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 x 4 conditions x 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.

5.5.1 *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 [Phillips et al., 1975].

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.

5.5.2 *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.

5.6 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 x 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 [Cumming, 2014] [Dragicevic et al., 2014], 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. 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.

5.6.1 *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

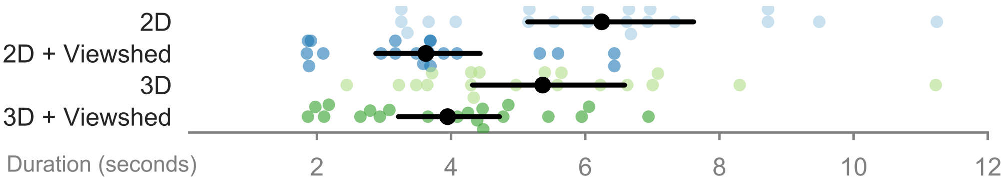
= [4.42, 6.31]). However, with the aid of the *dynamic viewshed*, participants were substantially faster – spending on average 3.44 seconds (CI = [2.68, 4.20]) in the *2D + viewshed* condition and 3.95 seconds (CI = [3.26, 3.95]) in the *3D + viewshed* (Figure 26).

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.

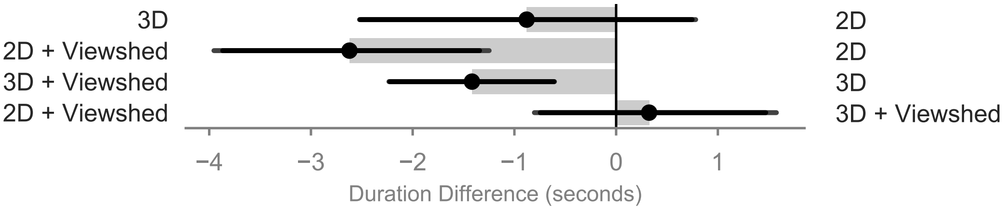
Participants gave binary Yes / No responses to the mutual visibility questions, from which we computed each participant's average accuracy rate. Although participants performed well in all conditions, the plain *2D* map produced the worst results, with an average score of 83% (CI = [71.1%, 94.9%]). Results 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 28). However, only the comparison between the *3D* and *3D + viewshed* conditions showed a clear difference.

5.6.2 *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 26). 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.



(a) Duration (shorter is better). Each dot shows data from one participant.

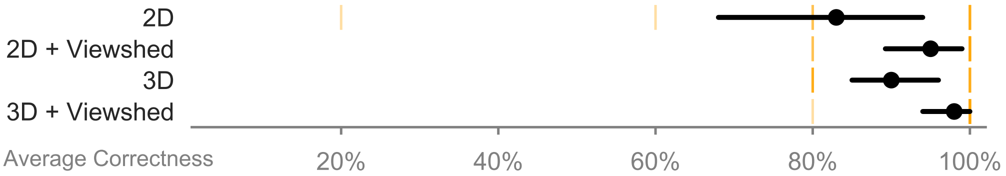


(b) Pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

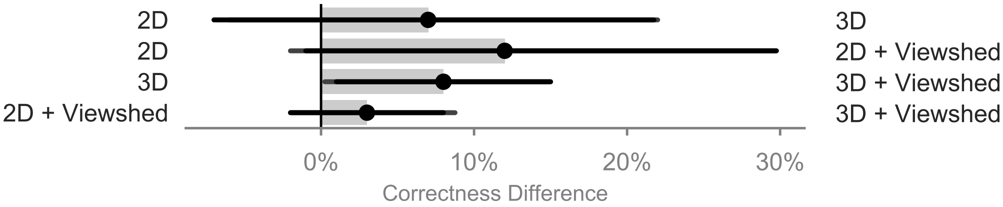
Figure 26: Study results: duration of line-of-sight trials

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 29). In pairwise comparisons, the *3D + viewshed* model clearly outperformed both the plain *3D* and *2D + viewshed* variants.

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

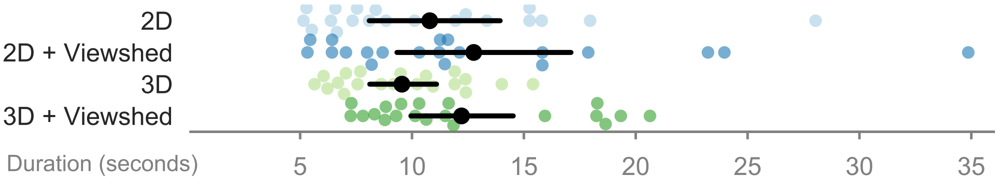


(a) Accuracy (higher is better)

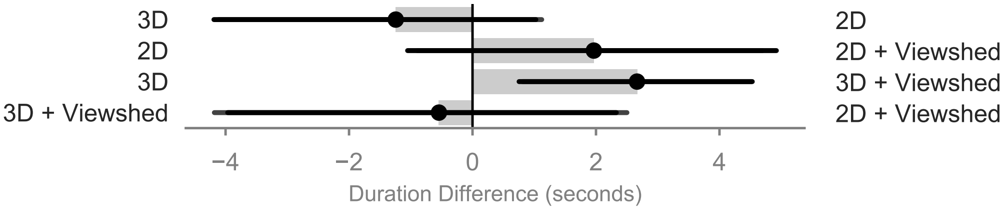


(b) Pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

Figure 27: Study results: accuracy of line-of-sight trials

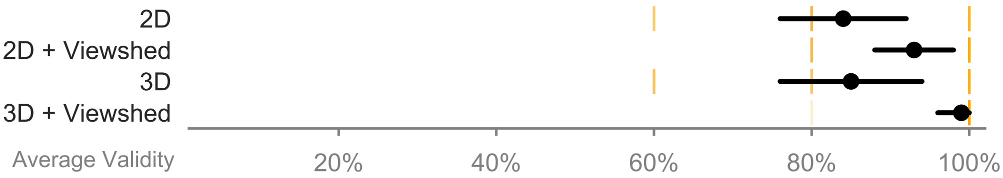


(a) Duration (shorter is better). Each dot shows one participant.

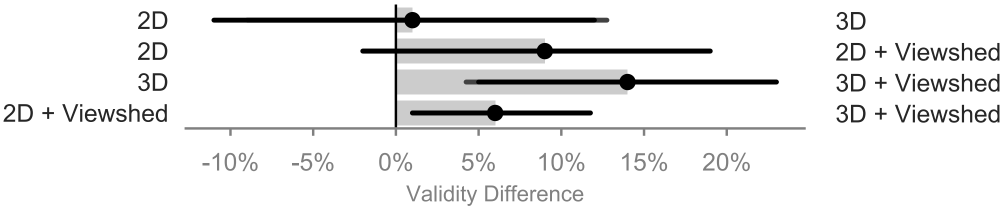


(b) Pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

Figure 28: Study results: duration of lowest-visible-point trials



(a) Accuracy (input validity) (higher is better)



(b) Pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

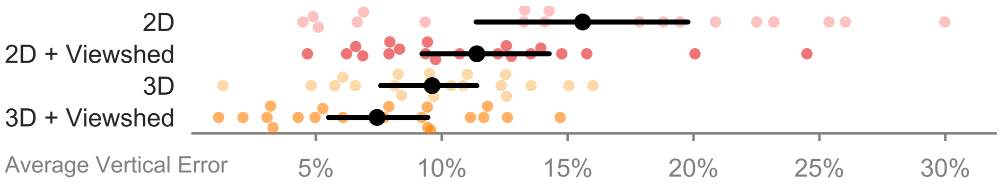
Figure 29: Study results: accuracy (input validity) of lowest-visible-point trials

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.

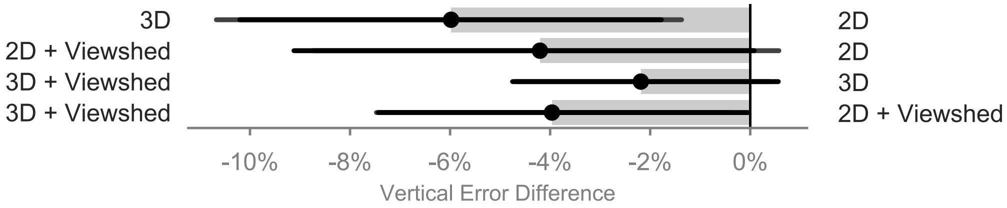
When using the plain *2D* map, participants' average error ratio was 15.6% (CI = [12.0%, 19.2%]). However, this dropped to 11.4% (CI = [9.1%, 13.7%]) in the *2D + viewshed* condition. On the plain *3D* model, average error was 9.6% (CI = [7.9%, 11.3%]) and dropped to 7% (CI = [5.6%, 9.3%]) in the *3D + viewshed* case (Figure 30). 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*).

5.7 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



(a) Accuracy (input validity) (higher is better)



(b) Pairwise comparison between conditions. Error bars show 95% CIs with a Bonferroni correction.

Figure 30: Study results: accuracy (input validity) of lowest visible point trials

viewsheds to both 2D maps and 3D models allowed participants to complete the tasks considerably more quickly and with very high accuracy (Figure 26 & 28).

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 29 & 30). 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.

5.7.1 *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 31) 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.)

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"

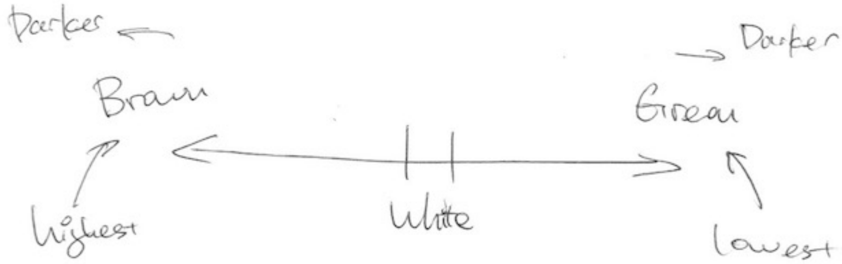


Figure 31: A participant of the study drew a color spectrum to help interpret the tint pattern on the 2D topographic map

(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).

5.7.2 *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 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 32). 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 touchscreen (such as zooming or rotation) as in other tablet-based mapping applications like

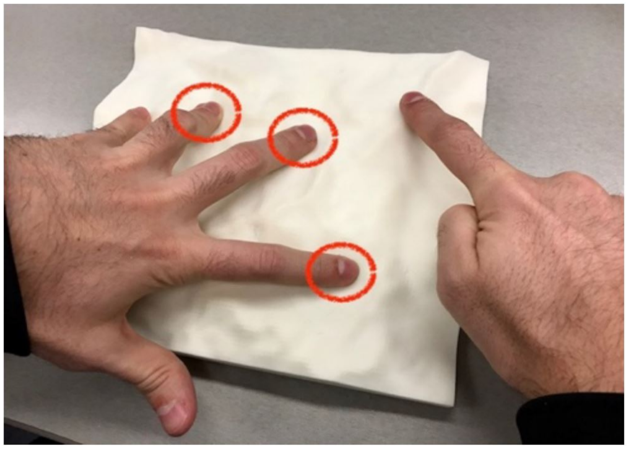


Figure 32: Participants of the study often used multiple fingers to track temporary decisions before reaching a final judgment

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.*

5.7.3 *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.

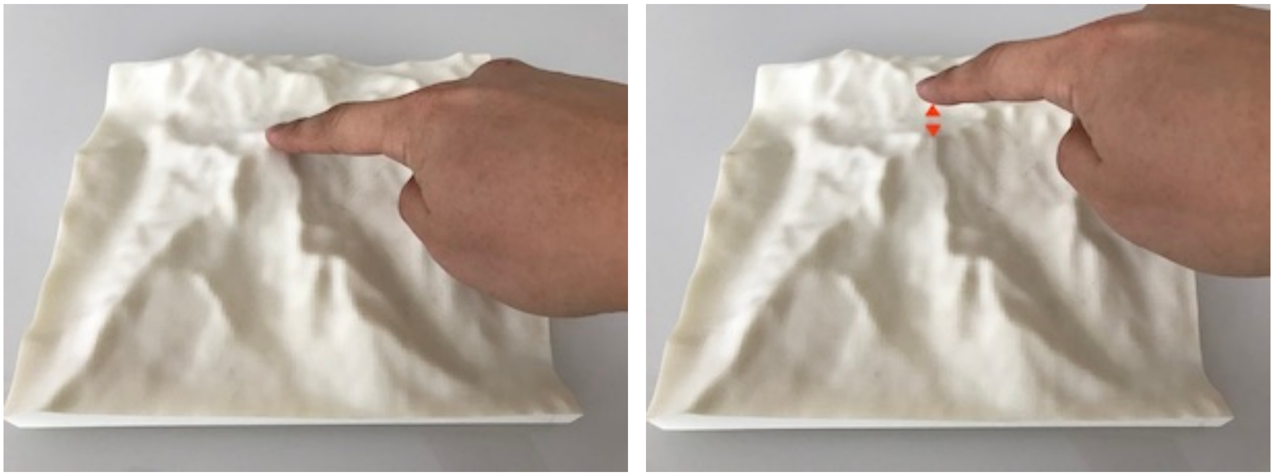
However, 5 out of the 20 participants kept their fingertips floating a couple of centimeters above the topographic surface, without direct contact with the map model. Interacting this way, participants experienced no friction on the surface of the model. One participant (P8) specifically emphasized a 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 33) 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.*

5.7.4 *Problems with Touch on Complex Models*

We also observed that particularly rough and complex areas of the 3D model (like those highlighted in Figure 34) were sometimes difficult to touch or manipulate directly.



(a) directly touching the map model

(b) hovering above the map model

Figure 33: How participants of the study interact with the dynamic viewshed on the 3D terrain model

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 [Roudaut et al., 2011] and interaction with physical visualizations [Jansen et al., 2013].

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

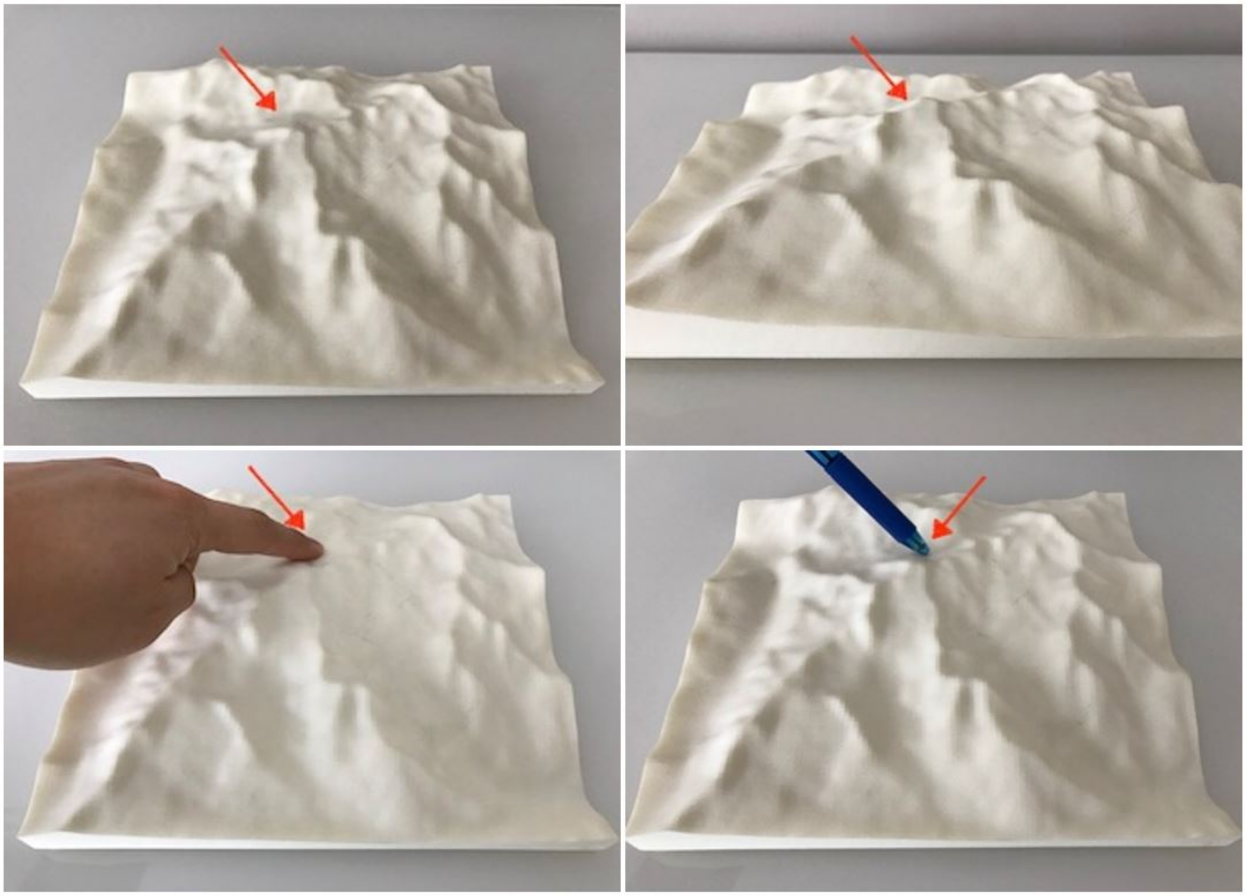


Figure 34: A location on the 3D physical map model with a lower elevation can be visually or physically occluded

5.8 DESIGN GUIDLINES

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.

5.8.1 *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 35). 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.

Figure 35: Terrain model at Maligne Lake, Jasper National Park, CANADA

5.8.2 *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.

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.

5.8.3 *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.

5.9 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

Figure 36: Out study considers hand-sized terrain models rather than larger terrain models where direct touch interactions can be more difficult

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 36) or smaller displays. Additional studies may be necessary to assess the generalizability of these techniques for maps of varying sizes.

5.10 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 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.

6

THESIS CONCLUSION

This dissertation has been an exploration of the interactive tangible topographic map in the form of a collection of five (4) publications (*Shvil*, *Flying Frustum*, and *Duopography*, and the user study). Among them, *Shvil*, *Flying Frustum*, and *Duopography*, grouped in Theme #1, have realized the concept into applications in various domains to show the feasibility of replacing traditional topographic maps with an interactive tangible alternative. In Theme #2, a user study was reported to systematically prove the benefit of using such a novel interface, resulting in a better understanding of the spatiality with a lower cognitive effort from the users.

In addition, there is an extra publication, located at Theme #3 in the appendix, involved a more extensive exploration of applying the interactive tangibility to higher-dimensional visualization and data-manipulation. However, due to its lower proximity to the main topic of the dissertation, which is the expriment of the physicality and tangibility of traditional topogaphic maps, it is not included in the main body of this thesis.

As a result, this thesis constitutes the advancement of the knowledge in both topographic Cartography and Computer Science, and the high-level contributions of this thesis are as follows:

1. A new interactive topographic interface (as known as the **interactive tangible topography**) that provides the user with immersive experience and interaction using a) a physical map model, and b) dynamic data visualization, superimposed on the model surface, based on user interaction in real-time. This physicalizing the spatial and topographical knowledge into tangible entities for users to easily grasp.
2. Use the aforementioned **interactive tangible topography** interface as a testbed to validate the hypothesis that the combined effort, of 3D physicality and augmented visualization, increases the legibility of the topographic maps, by providing the user solid and comprehensive spatial and situational awareness.
3. A new research methodology that potentially bridges between Computer Science and Cartography. Recently developed HCI techniques can provide new avenues to improving classic topographic map-reading tasks, and the insights gained during the process may further contribute back to HCI research.

This manuscript-based dissertation presents a new direction to evolve topographic cartography with modern technologies to improve the readability of the maps, advancing the knowledge of map usefulness in terms of representing spatial and situational awareness with lower cost of training and effort. Certainly there are a number of sub-disciplines in interactive cartography with physicality and this thesis was only able to briefly touch the surface and set a stage in such a direction. However, it is a promising method to bridge two significantly distinguishable areas, traditional media of map representation and rapidly-changing methodologies in interactive data visualization and interaction, and researchers in related fields should be encouraged to explore how the topographic map interface can further be enhanced and enriched to provide a better user experience.

Furthermore, this manuscript-based dissertation concludes my PhD study, which is also the foundation of our future academic research in Human-Computer Interaction. This is a report of what we have learnt during the process; that is, not to repeat what it has been, but to imagine what it could be.

6.1 LIMITATIONS OF THE INTERACTIVE TANGIBLE TOPOGRAPHY

This dissertation represents limited aspects of the entire scope of the physicalized topographic map. This is duo to the methodology used in the interactive tangible topographic map, especially the selection of its physical map model. In the next a few sections I will discuss the limitations of our current setting and the reasons and consequences behind those limitations. However, I argue that these limitations do not prevent us from grasping the big picture.

6.1.1 *Size of the Physical Map Model*

In this dissertation, a 20-cm-by-20-cm map model made from hard plastic was used as the physical representation of the terrain topography. Though the tangible map surface provides an easy understanding of the represented terrain topography, the physical size of the map model does introduce certain restricts that make the methodology less applicable upon generic tangible topographic maps.

The dimension of the map model is similar to the size of a stretched hand of a grown-up human, meaning any adult user of the interactive tangible topographic map can easily simultaneously reach to and cover any point on the map surface with using

Figure 37: Different map sizes may impact user interaction methods

one of or both hands. In fact, it is noticed that during the map study (see Theme #2), participants situated their individual fingers on previous point-of-interests as temporary references, especially during tasks that involve elevation comparisons. On the contrary, this method would be infeasible on larger maps that beyond the coverage of human hands. Users may still traverse the map surface with fingertips and get direct tangible feedback of the elevation, but situating fingers as reference points will be hard, if not completely impossible. (Figure 37)

This means different sizes of the physical map model might lead to distinguishable interaction methods, yet we believe it does not contradict with increased readability from the physicality and tangibility of the map.

6.1.2 *The Cost of Physical Map Usage*

Another limitation of the physical map model comes from its cost. The map model used through this dissertation was a 3D-printout from a single piece of solid material, rendering it impossible to be reused as maps of other geographical regions. However, we foresee the future that, similar to how paper printing had become significantly inexpensive, the cost of 3D-printing will decrease rapidly so that, at one day, printing physical maps will no longer be a concern, from a economic perspective.

A different approach to resolve this problem is making the physical map, or the tangible topographic map surface, reusable. Like how flat paper map has evolved into touchscreens that can display dynamic map contents, the physicality of the touchscreen surface might become dynamic as well, resulting in a shape-shifting tangible surface that can turn into different geometry for different terrain topography. With using such a device, the touch surface itself will play the roles of not only a dynamic visualization display, but also a direct tangible representation of the topography.

6.2 FUTURE WORK

6.2.1 *Other Possible User Studies*

Physicalizing topographic maps is a broad topic. Previous traditional topographic map research has shown that there is no single universal map representation that is feasible for all map reading tasks. Instead, to maximize the map legibility, specific visualizations need to be chosen based on the nature of the current task. In Theme #2, we reported a user study that revisited visibility tasks on topographic maps, and concluded that map

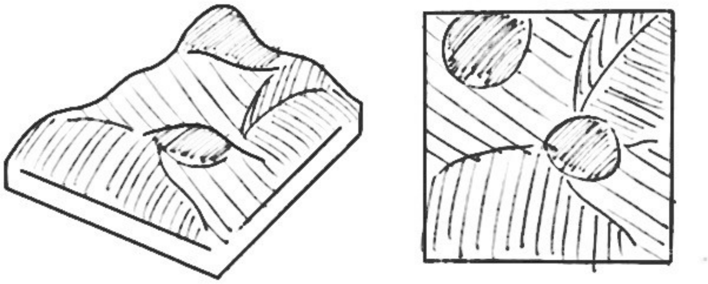


Figure 38: Other possible user study 1: color coding based on angles of slopes

tangibility did ease map users, especially whom with limit background, from reading complicate topography. Similarly, to understand how much benefit the tangible topographic interface may provide in other map reading tasks, it requires more specifically arranged user studies, presumably one for each task type. Therefore, one possible direction of the future work is to design and run different studies upon various common map reading tasks, to gradually learn in which area of topographic map representation the interactive tangible map interface is most suitable.

In the next a few paragraphs, I will address a couple of possible **map study designs**, all using the interactive tangible topographic map interface, to tackle some common map reading tasks. Hopefully, after running these studies, our knowledge of the readability of the new interface in comparison with flat maps can be further expanded.

6.2.1.1 *Study Design: Angle of Slopes*

It is always a challenge to represent continues elevation changes on flat topographic maps. Here we design a study to determine whether the 3D representation provides a better visual cue to the steepness at any given location, and regions with different angles of slopes are rendered in different color-coding.

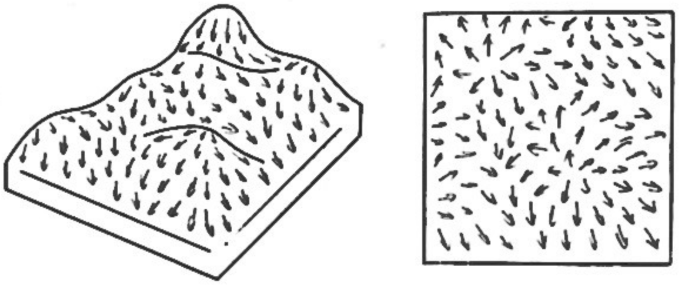


Figure 39: Other possible user study 2: overlay vector field on physical model for flow visualization

In the design of this user study, each participant will be asked to estimate and report numerical values of slope angles and compare the steepness between two slopes on both a traditional map and the new map interface. We hope such as arrangement provides not only immediate awareness of the slope at any given point on the map, but also yields sensible feedback of the magnitude of the slope reflecting the angle of the slope directly (Figure 38).

6.2.1.2 *Study Design: Vector Field for Flow Visualization*

In previous flat map study, a common task was asking participants to draw hypothetical rivers [Phillips et al., 1975]), starting from a given point on the high ground. The goal is to test the intuition of a regional elevation comparison (of finding the lowest point in this case). We assume that having the physical map model provides users the advantage of understanding the regional topography, which significantly helps the user to determine the flow of the river.

In addition, since the interactive tangible map interface is able to render dynamic visualization, it may provide vector fields to further enhance the tendency of changes in elevation. Vector fields are commonly used to show flow simulation, in which the tangent vector of any point on the map represents both magnitude and direction of the potential flow. A vector field on 2D-surface is complicated and hard to grasp the embedded meaning, but when displayed on the physical model it becomes quite obvious (Figure 39).

In the design of this study, we will repeat the classic study and ask participants to draw hypothetical rivers, only this time it is on a 3D physical terrain model superimposed with a vector field of flow visualization. We plan to collect the performance and accuracy of the completion of the task, compared with using flat topographic maps.

6.2.2 *Beyond Maps*

This thesis focused on tangible topographic maps, even though the enhancement of spatial awareness using physicality and tangibility is applicable to other applications and domains beyond the scope of map representations.

For instance, higher-dimensional geometric representation can be a good candidate of alternative reseach direction of enhancing spatial awareness with tangibility, in which natural perception helps to apprehend the hindered spatiality and prevents it from further distortion when displayed in lower-dimensional media. We barely touched the surface of it and reported a system for visualizing basic 4D geometries in Theme #3 (located in the appendices), yet found the result interesting and promising.

Moreover, both the physical representation and rich visual augmentation technologies are evolving rapidly. Imagine one day, instead of having a static printout model, we may have a dynamic physical entity with the shape-shifting capability. Furthermore, such a dynamic entity could also be covered with flexible display and touch sensors, allowing real-time gesture input and visual response over its dynamic physical interface.

With the aids of augmented visualization, this will be an extremely powerful solution to reflect the geometry and physicality of any given concept of the spatiality. At this point, natural perceptions of humans will be completely delivered with no distortion or compromise, since nothing is more familiar to us than holding a real physical object in our hands.

The real voyage of discovery consists not in seeking new landscapes but in having new eyes.

– Marcel Proust

Appendices

Part III

THEME #3: SPATIAL AWARENESS AND IMMERSIVE INTERACTION BEYOND MAPS

A

AND HE BUILT A CROOKED CAMERA: A MOBILE VISUALIZATION TOOL TO VIEW FOUR-DIMENSIONAL GEOMETRIC OBJECTS

A.1 PREFACE

In this chapter we move away from the topographic map domain and step into a bigger scope that expands the concept and apply it to intuitively visualize higher dimensions. We seek an approach to metaphonically represent 4D geometric shapes with immersivity and tangibility, and then introduce the experience in a story-telling [Li et al., 2015b]. The contents of the following sections are from the original publication but reorganized to fit in the structure of the dissertation.

A.2 INTRODUCTION AND MOTIVATION

> - *"Maybe they are to you, brother, but they still look crooked to me"*
>
> - *"Only in perspective, only in perspective."*
>
> – Robert A. Heinlein's And He Built a Crooked House

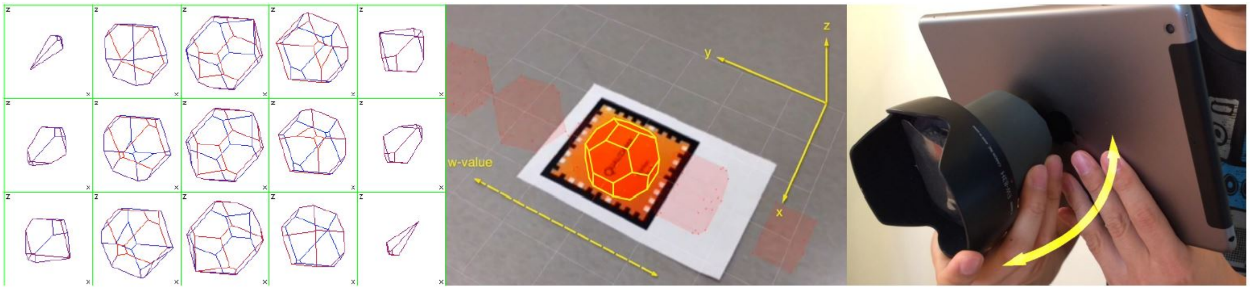


Figure 40: Explore projections of 4D shapes in full 3D with a natural perception and uses a camera-lens-style tangible interface to manipulate the 4th dimension

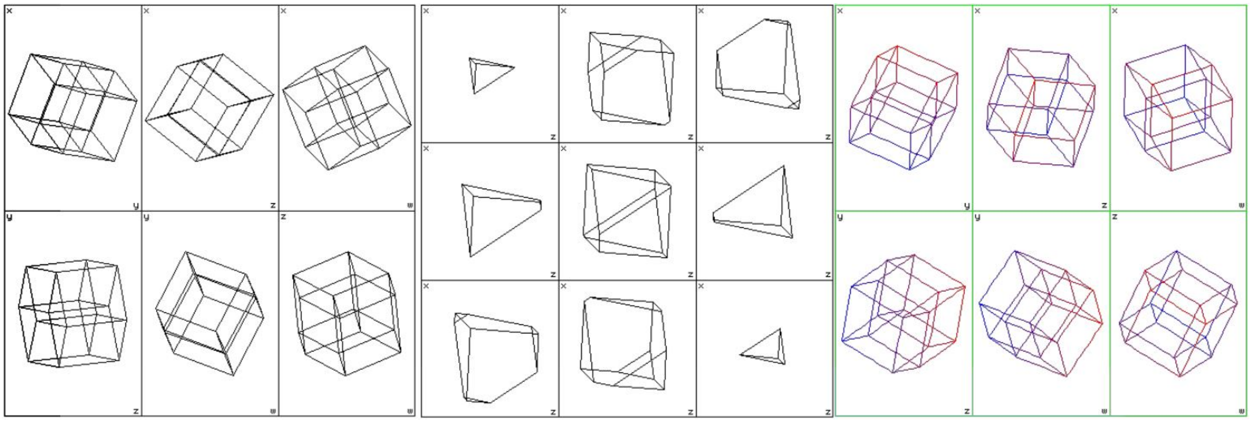


Figure 41: Visualization of a Tesseract with existing methods: Parallel Projections, Slices, and Depth Cue

There are several existing approaches to visualize 4D geometric objects, including Projection (Parallel, Perspective, or Stereographic), Slice, and Depth Cue (Figure 41 (from left to right)). Though these techniques can display 4D objects in a relatively straightforward and informative way, they require a steep learning curve and experience to fully understand the components of the visualizations (how the vertices, edges, faces, etc., are related). Ultimately, we argue that the under-standability of these techniques is limited, as the geometric representations do not match our natural perception and experience; they, as Heinlein's character complained when observing the design of a 4D house, "look crooked."

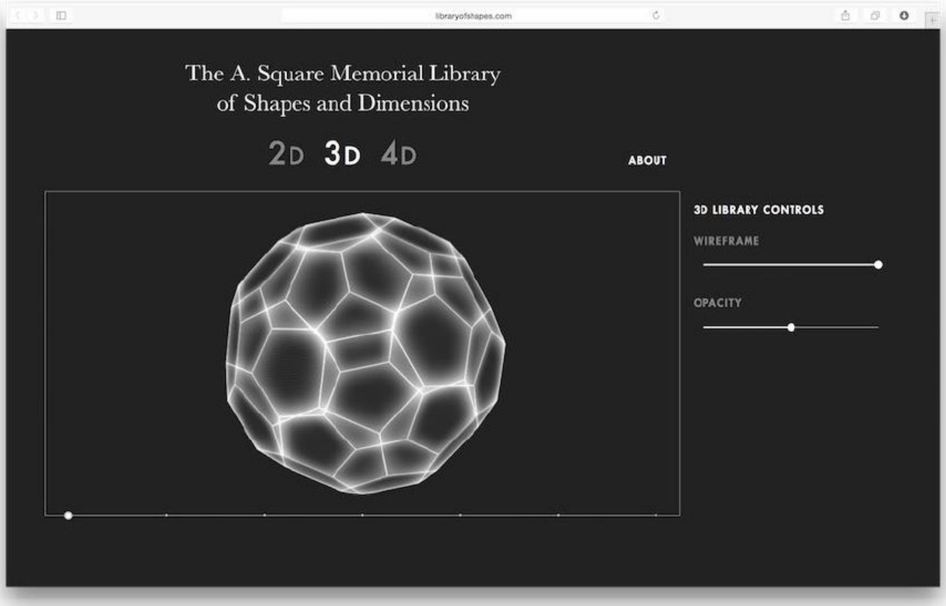


Figure 42: Typical interactive interface of 4D objects, in which all controls upon the hyperspace are operated on a 2D screen, in addition to the complicated camera manipulation

One limitation of presenting 4D geometric objects is that they are projected onto 2D surfaces (e.g., paper or a display). Our goal is to capture as much of the original geometric structure as possible while minimizing destruction of perspective or loss of information, although a perfect mapping is impossible due to the limits of human perception. In general, traditional approaches, along with their animated variations rendered in computers (Figure 42), either remove one or more dimensions to show an incomplete geometric structure (e.g., the Slice technique), or error is introduced into a shape's perspective by squeezing 4 dimensions into 2 (e.g., as with all Projection techniques and Depth Cue) (Figure 40 left, Figure 41). While such losses of information may be acceptable for simple geometric objects such as a Sim-plex (4D triangle), more complex shapes lead to larger error or information loss in consequence, hindering the visualiza-tion. For instance, the details of the Tesseract (4D cube, shown in Figure 41) are clear, but with traditional visualization techniques, complex shapes such as the 24-cell (Figure 40 left) are much more difficult to parse.

Our solution for visualizing 4D geometric objects uses a combination of a camera-lens-style physical input (Figure 8 right) and a mobile looking-glass-style display: the mobile display enables users to naturally observe the 3D intersections of the original 4D shape in the higher dimension while benefiting from spatial freedom, i.e. being able to explore it from any arbitrary view angle, while simultaneously exploring the fourth dimension by controlling a physical device. We use a camera metaphor, where a person looks through the camera to view the 4D object, and turns the zoom ring on the lens to shift the visualization along the 4th dimension. For the remaining spatial dimensions, our technique does not require any inherent dimension reduction or perspective distortion, which minimizes the abstraction of the original structure, and viewers are in full control of the exploration. We describe our prototype below.

A.3 RELATED WORK

Visualizing the geometric structure of different dimension-alities in intuitive and understandable ways has a long his-tory spanning literature [Abbott, 2006] [Heinlein, 1941] to geometry [Cleveland and Cleveland, 1985] [Rucker, 2012]. Comput-er graphics and animation techniques [Noll, 1967] [Sabella, 1988] [Hanson and Cross, 1993] later enabled viewers to interact and manipulate a 4D shape in its digital form [Ramírez and Aguila, 2002] [Aguilera, 2006] or even the physical form [Sequin et al., 2002] [Arenas and Pérez-Aguila, 2006]. The contribution of these existing techniques is how they simplify or predigest complicated 4D geometric structures. However, manipulating those

4D shapes by decomposing, unfolding, etc., inevitably incorporates a certain kind of dimension reduction and perspective distortion.

In this paper, we propose a technique that enhances the understandability of 4D shapes by reducing structural ab-straction, and leverages users' natural exploring experience.

A.4 METONYMY AND DESIGN INTUITION

Before diving into the unintuitive 4D world, let us first sim-plify the story by imagining how people living in a 2D world, as Edwin A. Abbott described in his novel "Flatland"[Abbott, 2006], visualize imaginary 3D geometric objects in an intuitive method. We keep the anatomic basis of the "Flat-landers" (2D people living in a 2D world) as in the original novel, but with 21st century technology.

In Flatland, 1D materials are used to preserve information (paper, book, display screen), and Flatlanders have no dif-ficulty understanding and reasoning about 2D structures, just as we are fully capable of appreciating the 3D world even though our display mediums are usually 2D (paper, book, display screen). Flatlanders have no concept of "up" and "down" along their theoretical z-axis, so when studying 3D geometry, they must look at 2D projections or slices of 3D objects. Conceptually, Figure 43 shows how a sequence of Slice graphs look like in a Flatlander textbook (1D pieces of paper) that introduces a 2-sphere (surface of ball), which is a 3D object and a hyper-object for Flatlanders.

By only observing discrete "key frames" (the slices or projections) along the hyper-dimension, Flatlanders may find it hard to mentally reconstruct the continuous geometric shape because they cannot perceive a z-axis. In Figure 4, the key frames are 2D pro-

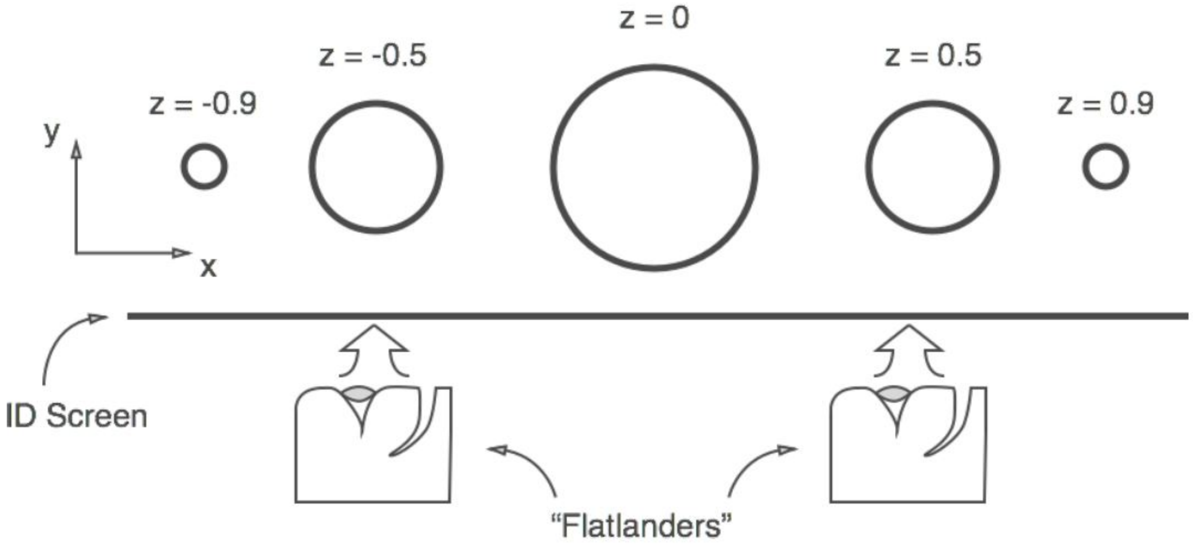


Figure 43: Slice graphs of a 3D object on a Flatland textbook

jections of the 3D hyper-object, shown as individual circles, but they need to be further abstracted in order to fit into 1D display mediums in Flatland.

Fortunately, in this 2D parallel universe of ours, virtual 2D objects can be illustrated situated at a fix position, allowing Flatlanders to walk around it with 1D "see-through device" and observe it in the Flatlanders' natural 2D perspective, as if a physical 2D entity is being displayed (Figure 44). This idea is similar to "augmented reality", as a virtual object is "pinned" at a fixed position in the space, allowing people to observe it while maintain spatial freedom. However, we use the term "visualization" rather than "augmented reality" because in a hyperspace there is no "reality" for us to augment.

To illustrated 3D hyper-objects, the Flatlanders extract one of the axes, the z-axis in our story, from the hyperspace. At any z-value, the corresponding x-y space contains a 2D intersection of the original 3D shape, just like for a regular 2D object spans in the xy-space, any given x-value corresponds to a y-value. Here any 2D intersection can be illustrated with the aforementioned "augmented reality"-like visualization, providing

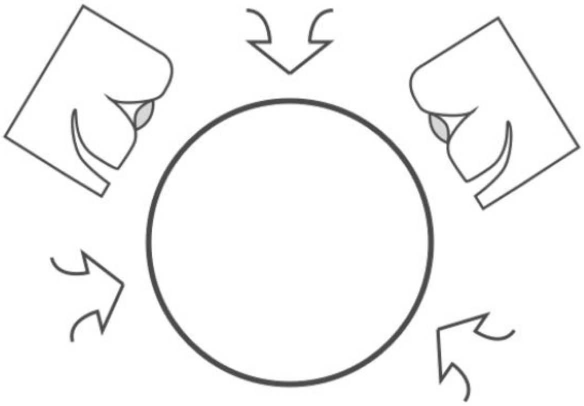


Figure 44: "Augmented reality"-like visualization in Flatland

full spatial freedom to take advantage of Flatlander's natural perspective, enabling them to explore the 3D shape with a spatial experience that is similar to how they explore their own 2D world every day (Figure 44).

The crucial piece of the puzzle is to design an informative method of letting Flatlanders manipulate the hyper-axis with their hands (or tentacles, depending on what they have), without overlapping or interfering with any physical axis — the x- and y-axis in Flatland — in order to maintain a natural viewing experience. We use a camera metaphor: a photographer moves in space to point-and-shoot, and can adjust the aperture to change the focal depth, considering focal depth as an extra dimension. Flatlanders adopted the metaphor of the camera lens as a physical interface to update the z-value dynamically. Thus, "focusing" the camera lens changes the z-value of the corresponding 2D intersection (circles) of a 3D shape (sphere) in real time (Figure 45).

Another goal is maintaining a sense of continuity of the hyper-object, or how the hyper-object will change while browsing along the z-axis. In order to help maintain an overall understanding of the original geometric structure, we display key frames as ghost images at selected z-values (dashed lines in Figure 6). In other words, the Flatland

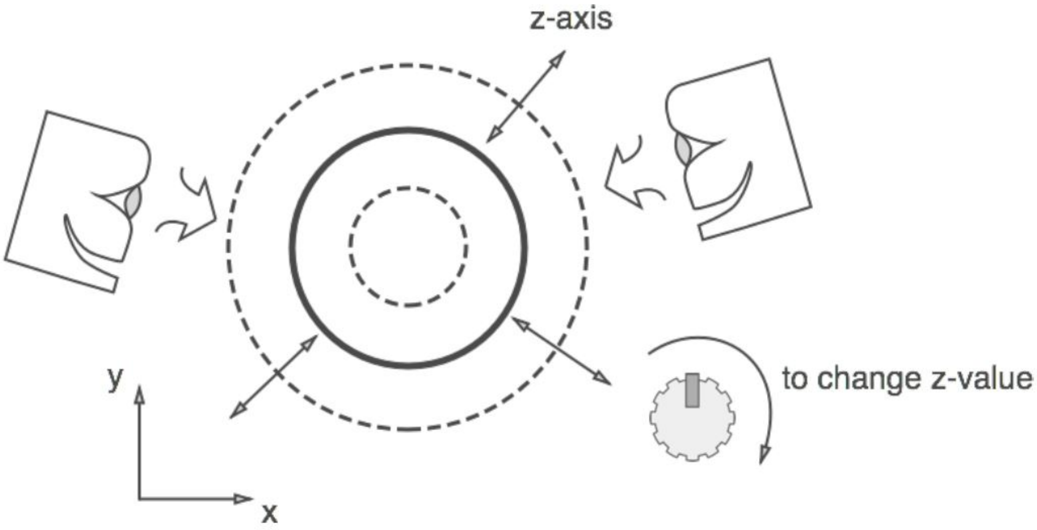


Figure 45: "Augmented reality"-like visualization allows Flatlanders to change the hyper-axis dynamically

user always knows how the object would change after increas-ing or decreasing the z-value. This removes the need to constantly rotate the lens, and rotation becomes a tool that provides continuous visualization to link the dots together, helping the Flatlanders understand how the hyper-shape changes in between the key frames.

In summary, by using the aforementioned visualization technique, a hyper-object's x- and y-axis, the real spatial dimensions in Flatland, are preserved without any perspective distortion and can be observed with their natural spa-tial freedom. Perception and manipulation of the addition-al hyper-dimension, the z-axis, is delivered by physical interactions with continuous illustration. In this way, all spatial awareness of the 3D hyper-object is preserved. Also we designed the manipulation of the hyper-dimension to be separated from the fundamental, or "real", x-y space, so that exploring the hyper-object won't be confused with updating the z-value. Hence, both of our goals, which are no dimension reduction and perspective distortion, are achieved, and Flatlanders may better understand the essence of a hyper-dimensional 3D object and live ever happily after.

Now let us travel back to our 3D world and apply the same approach; that is, use a similar concept to illustrate a 4D geometric structure, spanning 3 fundamental spatial dimensions plus one hyper-dimension, with no dimension reduction and perspective distortion, in order to provide a more intuitive yet informative way to appreciate a given 4D geometric object.

A.5 IMPLEMENTATION

We use an iPad Air as the "looking glass" device, and the application is implemented with the Qualcomm Vuforia library. A physical marker is used to situate the center of the rendering in the real world. The device captures both the location and orientation of the marker and renders vir-tual images correspondingly, as if a physical model has been placed on the marker.

To demonstrate the system, we use a 24-cell, a regular poly-tope in 4D with 24 octahedral cells, 96 triangular faces, 96 edges, and 24 vertices. Due to the complexity of its geo-metric structure, it is very difficult to understand it with traditional projection techniques. Also, it will be very dense to display all the vertices, edges, and faces in a surface of a limited size (Figure 46).

Similar to our Flatland story, the w-axis in the 4D space is extracted and the user is enabled to adjust its value. Then, the remaining 3 dimensions (x, y, and z) span a regular 3D space. At any given w-value, it is guaranteed by our design that the corresponding 3D intersection can be illustrated without visual distortion, with all the spatial information and freedom maintained (Figure 47).

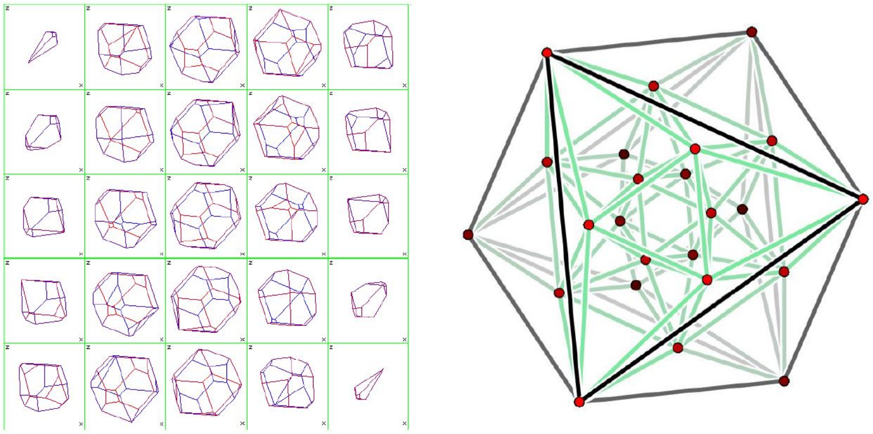


Figure 46: Traditional approaches to visualize a 24-cell

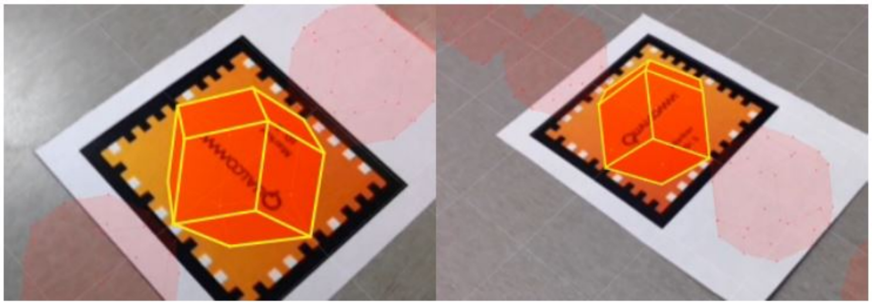


Figure 47: The camera-like interface illustrates 3D projections at any given value on the hyperaxis with a natural perception

Moreover, we also constructed a camera lens-looking phys-ical interface with a Phidgets rotation sensor mounted at the back of the tablet, providing the aforementioned pseu-do-camera experience of interaction (Figure 40 right). While walking around the visualization of the 3D model situated at the marker, the user can rotate the lens to increase or decrease the w-value, triggering the embedded rotation sen-sor to update the w-value and the rendered 3D intersection accordingly. As the w-value varies, the smooth real-time transformation of the 3D intersection gradually delivers the idea about the overall geometric structure of the original 4D shape to the user (Figure 48), as Flatlanders

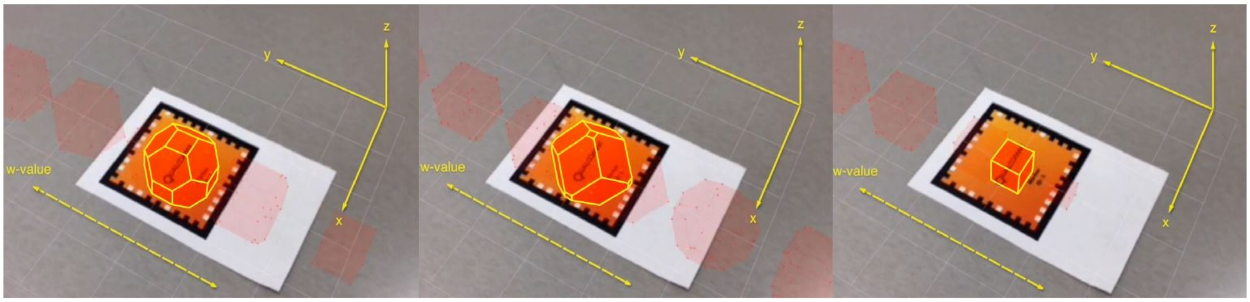


Figure 48: The camera-like interface allows the value along the hyper-axis to be changed with the tangible interface continuously and dynamically

see the expan-sion and contraction of the circle and receive a better understanding of the sphere.

Key frames, represented as ghost images, are also provided at a few selected values (w = -100%, -50%, 0, 50%, 100% of the value), to give the user a hint of how the particular 3D intersection will look after increasing or decreasing the w-value without changing the lens physically. Theoretically, in 4D, these 3D key frames are stacked together like nested dolls, as circles with different radii are positioned at the same center to present key frames of a sphere in the "Flatland" story (Figure 45). However, when many ghost images overlap, it becomes chaotic and difficult to look at (remember, in the "Flatland" story we looked at stacked circles from the third, hyper dimension of their world); thus, we distribute those key frames in a row. The 3D intersection is always situated at the center of the display area, while key frames shift linearly based on the magnitude of the change such that a corresponding key frame coincides with the intersection when both w-values are equal (see ghost images in Figure 9).

A.6 CRITIQUE

We have run a primarily critique session with a small group of participants who have higher education background but not majored in Mathematics. We selected such a target group due to their sufficient knowledge of Mathematics and Geometry but not too much familiarity with hyperspaces.

All participants are able to operate our prototype application independently after a very short training. Participants reported that the "augmented reality"-like observation me-chanics are easy to perform and relieve them from tedious and complicated camera manipulation, which is what they commonly deal with on regular display screens. Also, participants understood the camera lens metaphor instantly and had no difficulty operating it, which is the original pur-pose of our design.

In summary, participants thought the application was "fun", "controllable", and "straight-forward", and helping them to obtain the basic spatial knowledge of 4D geometric structures with experiencing a "less steep learning curve". Moreover, besides improving perceptual easiness, the freedom of maneuvering and applying natural observations made them feel "more confident and masterful", and such a psychological influence is beyond our expectation and we are interested in interpreting it in our future experiments.

A formal study will be necessary for more insight, but even this small critique session suggests the potential of the system as an easy to use, tangible interface to explore hyperobjects.

A.7 CONCLUSION AND FUTURE WORK

We present a mobile prototype visualizing 4D geometric objects using a physical camera-like interface. We consider the following directions for future exploration.

One thread will be applying the same concept to more irregular and complex 4D geometric structures, in addition to the symmetric 4-manifolds that we used to validate our concept in this paper.

Another avenue is higher dimensional visualization. Our method may be scalable to visualizing geometry in 5, 6, or more spatial dimensions, or maybe even a spacetime such as the Minkowski space-time continuum. If the simplicity and comprehensibility of our method decreases in these cases, then we need to explore extending the technique to maintain its characteristics in these deeper hyper-dimensions.

We would like to evaluate our prototype via a user study, collecting qualitative and quantitative data related to the intelligibility of the method when observing and studying a 4D geometric object or structure compared to traditional visualization techniques, or even the pure text-base nota-tions that only make sense to experts. Furthermore, it will be interesting to observe two participant groups with different expertise level use our tool, one with sufficient amount of mathematical knowledge and one without, and see whether our interface provides additional insight to either of the groups.

In summary, we presented a new method to illustrate and interact with 4D geometric objects. We carefully designed the visualization to provide the user with a familiar visual representation of the 3D intersection of the object without distortion, enabling free spatial exploration, and allowing the fourth hyper-dimension to be controlled and manipulated by the user who is continuously and dynamically up-dating the 3D intersection.

We hope that our method and prototype could set the stage and inform future research on this topic, potentially bringing this design concept to help illustrate high-dimensional scientific information.

Part IV

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- Nico Li, Stephen Cartwright, Aditya Shekhar Nittala, **Ehud Sharlin**, and Mario Costa Sousa. Flying frustum: A spatial interface for enhancing human-UAV awareness. In *Proceedings of the 3rd International Conference on Human-Agent Interaction*, pages 27-31. ACM, 2015.
- Nico Li, Daniel J. Rea, James E. Young, **Ehud Sharlin**, and Mario Costa Sousa. And he built a crooked camera: a mobile visualization tool to view four-dimensional geometric objects. In *SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications*, pages 23. ACM, 2015.
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- Nico Li, Stephen Cartwright, Ehud Sharlin, and **Mario Costa Sousa**. Ningyo of the CAVE: robots as social puppets of static infrastructure. In *Proceedings of the second international conference on Human-agent interaction*, pages 39-44. ACM, 2014.
- Nico Li, Aditya Shekhar Nittala, Ehud Sharlin, and **Mario Costa Sousa**. Shvil: collaborative augmented reality land navigation. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 1291-1296. ACM, 2014.

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- Nico Li, **Stephen Cartwright**, Ehud Sharlin, and Mario Costa Sousa. Ningyo of the CAVE: robots as social puppets of static infrastructure. In *Proceedings of the second international conference on Human-agent interaction*, pages 39-44. ACM, 2014.

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- Nico Li, **Aditya Shekhar Nittala**, Ehud Sharlin, and Mario Costa Sousa. Shvil: collaborative augmented reality land navigation. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 1291-1296. ACM, 2014.

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Part V

DATA PROCESS OF THE STUDY RESULTS

```
In [1]:
```

```
import numpy as np  #load up the libraries and object defs. we need
import pandas as pd
from pandas import DataFrame, Series

# load up my visualization system, and call the object plt
import matplotlib.pyplot as plt
import seaborn as sns

# tell ipython notebook to print visualizations inline
%pylab
%matplotlib inline

from IPython.display import set_matplotlib_formats
set_matplotlib_formats('pdf','png')
```

```
Using matplotlib backend: MacOSX
Populating the interactive namespace from numpy and matplotlib
```

```
In [2]:
```

```
#Set formatting and styles
sns.set_style('ticks',{"ytick.major.size":0, "xtick.major.size":3,
                       "axes.edgecolor": ".5", "xtick.color": ".5",
                       "axes.labelcolor": ".5", "axes.linewidth":"1.0"})
base_colors=sns.color_palette("Paired", 10)
duration_colors = base_colors[0:4]
correctness_colors = base_colors[4:8]
```

Line-of-Sight Tasks

```
In [3]:
```

```
# Load Line-of-Sight dataset
los_data = pd.read_csv('log-lineofsight.csv',encoding="utf-8-sig")
```

```
In [4]:
```

```
# Create combined "Condition" field
for index, row in los_data.iterrows():
    los_data.loc[index,'Condition'] = row["Model"] + (" + Viewshed" if row["View
shed"] == "Y" else "")

# Group results by condition and participant and average durations
los_grouped = los_data.groupby(["Condition","Participant"],as_index=False).mean
()
los_grouped.sample(5)
```

```
Out[4]:
```

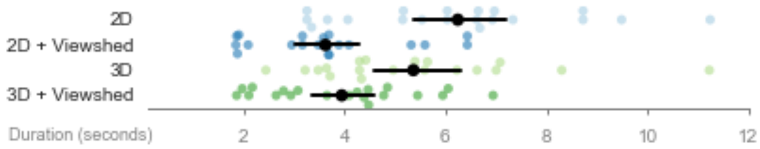
	Condition	Participant	Task	Correct	Duration
61	3D + Viewshed	2	3.0	1.0	4.253086
14	2D	15	3.0	1.0	8.724960
10	2D	11	3.0	0.6	6.930238
17	2D	18	3.0	1.0	9.487970
41	3D	2	3.0	1.0	7.083838

Duration

```
In [6]:
```

```
# Plot charts
fp = sns.factorplot(x="Duration", y="Condition", data=los_grouped,
                    color="black", join=False, size=1.5, aspect=4,
                    scale=0.65,errwidth=2)
plt.setp(fp.ax.lines, zorder=100)
plt.setp(fp.ax.collections, zorder=100)
sns.swarmplot(x="Duration", y="Condition", data=los_grouped, ax=fp.ax,
               palette=duration_colors, marker="o", size=5, linewidth=0,alpha=0.
6)

# Additional Formatting
sns.despine(left=True)
fp.ax.set_xlim(0.1,12)
fp.ax.set_xlabel('Duration (seconds)', fontsize = 9)
fp.ax.set_ylabel('')
fp.ax.xaxis.set_label_coords(-0.11,-0.18)
```



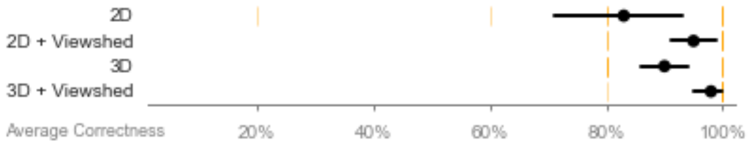
Correctness

```
In [7]:
```

```
#Plot charts
fp = sns.factorplot(x="Correct", y="Condition", data=los_grouped,
                    color="black", join=False, size=1.5, aspect=4,
                    scale=0.65,errwidth=2)
plt.setp(fp.ax.lines, zorder=100)
plt.setp(fp.ax.collections, zorder=100)
sns.stripplot(x="Correct", y="Condition", data=los_grouped, ax=fp.ax,
              color="orange", marker="|", size=10, linewidth=1,alpha=0.2)

# Additional Formatting
sns.despine(left=True)
fp.ax.set_xlim(0.01,1.02)
fp.ax.set_xlabel('Average Correctness', fontsize = 9)
fp.ax.set_ylabel('')
fp.ax.xaxis.set_label_coords(-0.105,-0.18)
fp.ax.xaxis.set_major_formatter(FuncFormatter(lambda x, _: '{:.0%}'.format(x)))

# Save PDF
fp.savefig("images/LoS-Correctness.pdf", transparent=True, bbox_inches='tight',
pad_inches=0)
```



Lowest Visible Point Tasks

```
In [8]:
```

```
# Load Lowest-Visible-Point dataset
lvp_data = pd.read_csv('log-lowestvisible.csv',encoding="utf-8-sig")
```

In [9]:

```
model_height = 31.68 #Height of the model (in Z-units)

# Create combined "Condition" field, convert isVisible to a "Correct" number,
#   and normalize DistanceZ based on total height of the model
for index, row in lvp_data.iterrows():
    lvp_data.loc[index,'Condition'] = row["Model"] + (" + Viewshed" if row["View
shed"] == "Y" else "")
    lvp_data.loc[index, 'Correct'] = (1 if row["DistanceZ-isVisible"] == "Y" els
e 0)
    lvp_data.loc[index, 'DistanceZ-Normalized'] = (row["DistanceZ"]/model_height
)


# Group results by condition and participant and average durations
lvp_grouped = lvp_data.groupby(["Condition","Participant"],as_index=False).mean
()
lvp_grouped.sample(5)
```

Out[9]:

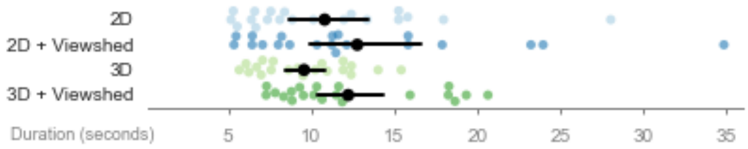
	Condition	Participant	Task	DistanceXY	Duration	DistanceZ	Correct	Distance Normaliz
47	3D	8	3	0.107216	7.689586	3.014	1.0	0.095139
53	3D	14	3	0.072332	10.935228	0.414	1.0	0.013068
73	3D + Viewshed	14	3	0.094292	10.637444	2.502	1.0	0.078977
19	2D	20	3	0.094680	15.253988	6.612	0.8	0.208712
11	2D	12	3	0.176982	6.640250	8.246	1.0	0.260290

Duration

In [10]:

```
# Plot charts
fp = sns.factorplot(x="Duration", y="Condition", data=lvp_grouped,
                    color="black", join=False, size=1.5, aspect=4,
                    scale=0.65,errwidth=2)
plt.setp(fp.ax.lines, zorder=100)
plt.setp(fp.ax.collections, zorder=100)
sns.swarmplot(x="Duration", y="Condition", data=lvp_grouped, ax=fp.ax,
               palette=duration_colors, marker="o", size=5, linewidth=0,alpha=0.
6)

# Additional Formatting
sns.despine(left=True)
fp.ax.set_xlim(0.1,36)
fp.ax.set_xlabel('Duration (seconds)', fontsize = 9)
fp.ax.set_ylabel('')
fp.ax.xaxis.set_label_coords(-0.11,-0.18)
```

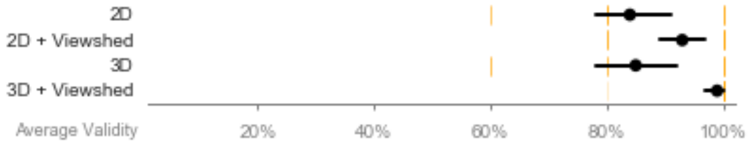


Validity

In [11]:

```
#Plot charts
fp = sns.factorplot(x="Correct", y="Condition", data=lvp_grouped,
                    color="black", join=False, size=1.5, aspect=4,
                    scale=0.65,errwidth=2)
plt.setp(fp.ax.lines, zorder=100)
plt.setp(fp.ax.collections, zorder=100)
sns.stripplot(x="Correct", y="Condition", data=lvp_grouped, ax=fp.ax,
               color="orange", marker="|", size=10, linewidth=1,alpha=0.2)


# Additional Formatting
sns.despine(left=True)
fp.ax.set_xlim(0.01,1.02)
fp.ax.set_xlabel('Average Validity', fontsize = 9)
fp.ax.set_ylabel('')
fp.ax.xaxis.set_label_coords(-0.12,-0.18)
fp.ax.xaxis.set_major_formatter(FuncFormatter(lambda x, _: '{:.0%}'.format(x)))
```

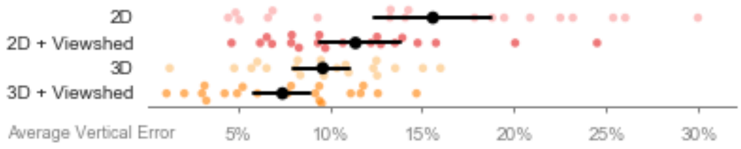


Vertical Error

In [12]:

```
#Plot charts
fp = sns.factorplot(x="DistanceZ-Normalized", y="Condition", data=lvp_grouped,
                    color="black", join=False, size=1.5, aspect=4,
                    scale=0.65,errwidth=2)
plt.setp(fp.ax.lines, zorder=100)
plt.setp(fp.ax.collections, zorder=100)
sns.swarmplot(x="DistanceZ-Normalized", y="Condition", data=lvp_grouped, ax=fp.a
x,
               palette=correctness_colors, marker="o", size=4.5, linewidth=0,alp
ha=0.6)

# Additional Formatting
sns.despine(left=True)
fp.ax.set_xlim(0.001,0.32)
fp.ax.set_xlabel('Average Vertical Error', fontsize = 9)
fp.ax.set_ylabel('')
fp.ax.xaxis.set_label_coords(-0.095,-0.18)
fp.ax.xaxis.set_major_formatter(FuncFormatter(lambda x, _: '{:.0%}'.format(x)))
```



Part VI

USER STUDY CONSENT FORM

UNIVERSITY OF
CALGARY

Name of Researcher, Faculty, Department, Telephone & Email:

Nico Li, Faculty of Science, Department of Computer Science, li26@ucalgary.ca

Supervisor:

Dr. Ehud Sharlin and Dr. Mario Costa Sousa

Title of Project:

Topographic Map Comparison between Classic 2D Flat Map and 3D Physical Terrain Representation

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This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The purpose of the study is to investigate how a 3D physical topographic map representation of terrain facilitates spatial perception. To address this issue, we conduct a cartographic comparison study between a 3D printed physical topographic map and a traditional flat topographic map. During the study, we ask participants to perform simple map reading tasks with using both types of maps, and provide feedback on their design and legibility. This will reflect the strength and weakness of using 3D physical topographic, when compared to classic flat maps, and determine whether it is feasibility to replace flat topographic maps with 3D physical representations in future projects that involves terrain navigations and field excursions.

What Will I Be Asked To Do?

To test our hypothesis, we will conduct a controlled within-subject experiment with 20 participants. The experiment will be conducted on the two interfaces. The first interface is a 2D map-based interface running on a tabletop computer. The second interface is a tangible user interface where a 3D printed model of the terrain is used as a physical topographic map. The information is superimposed onto the 3D printed model and the participants can interact with the 3D printed physical model with a fingertip. The methodology consists of the following steps:

1. *Participant will be introduced with the background and motivation of this study.*
2. *Participant will be given an opportunity to try both the tabletop and physical interfaces. (Training phase)*
3. *Once the participants are comfortable with the interfaces, they will be given line-of-sight tasks between two randomly-generated points (randomness is controlled based on specific criteria) on the map. The participant needs to determine the visibility between these two points, or to click/tap on the map to find the lowest location on the terrain which is visible from a given point. (Test Phase)*
4. *At the end of all trials, the participants will be interviewed about their experience on both the interfaces and their views and opinions would be useful in a qualitative analysis of our experiment.*

Participant will be completely anonymous, and no identifying information will be kept. Participant may withdraw from the study at any time. If the participant wishes to withdraw, the session will be stopped immediately and the participant will be thanked and debriefed. Possible questions of the participant will be answered. The data collected from that participant will be destroyed and not be included in the analysis of the study.

What Type of Personal Information Will Be Collected?

No personal identifying information will be collected in this study, and all participants shall remain anonymous.

Are there Risks or Benefits if I Participate?

Participant will be asked to perform interactions upon regular surface display and plastic 3D printout in an indoor environment; therefore, participant will experience risks that is no greater than everyday office work. However, if in any case the participant feels stressed or uncomfortable, study will be terminated immediately.

Participant will be paid CAD$20.00 once complete the study.

What Happens to the Information I Provide?

Participation is completely voluntary, anonymous and confidential. You are free to discontinue participation at any time during the study. No one except the researcher and his supervisor will be allowed to see or hear any of the answers to the questionnaire. There are no names on the questionnaire. Only group information will be summarized for any presentation or publication of results. The questionnaires are kept in a locked cabinet only accessible by the researcher and his supervisor. The anonymous data will be stored for five years on a computer disk, at which time, it will be permanently erased.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature: ____ Date: ______________

Researcher's Name: (please print) ____

Researcher's Signature: ____ Date: _____________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Mr. Nico Li
Department/Faculty of Computer Science
li26@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact the Research Ethics Analyst, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

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