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"I Can Physically Feel the Difference": Exploring Physicalizations of Running Data

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“I Can Physically Feel the Difference”: Exploring Physicalizations of Running Data

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

“I Can Physically Feel the Difference”: Exploring
Physicalizations of Running Data

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We explore user interactions with concrete physical visualizations—physicalizations—of personal experiential data. We conducted three user studies involving physicalizations of data gathered while trail running—a sport in which participants are largely more focused on the experience than the exercise itself. In two qualitative studies, we asked trail runners to give us a GPS path from a “significant run” and then prepared a 3D physicalization featuring the path overlaid as a raised line on the corresponding real-world terrain. In the first, physicalizations had a significant impact in helping participants recall memories of their experiences, and participants shared many stories. In a follow-up study, we found that participants told frequent stories when interacting with physicalizations and very few with paper topographic maps. In a third, quantitative study, we found that participants could identify features of a path in mountainous terrain with greater speed and accuracy on a 3D physicalization than on a paper map. We theorize that these physicalizations allow for a reduced cognitive load as compared to 2D topographic maps, leaving mental faculties free to recall stored memories.

Keywords: Human-computer Interaction, Visualization, 3D Printing

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Chapter 1

Introduction

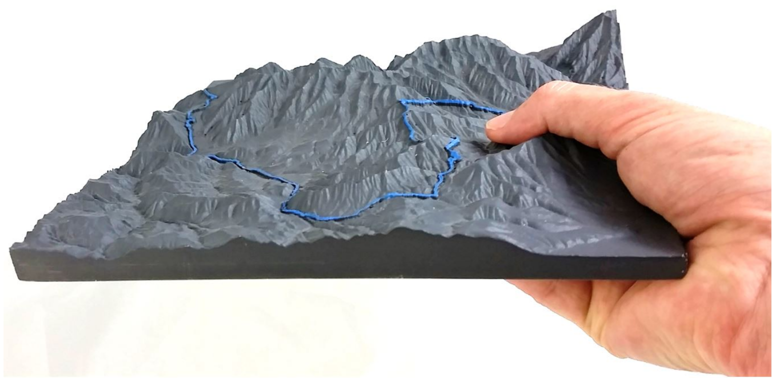


Figure 1.1: A physicalization of a person's route when running in the mountains.

We explore interaction with physicalizations of personal experiential data through the lens of trail running events. Trail running is a sport in which people run on unimproved trails in an outdoor or wilderness setting. Trail running is an ideal activity in which to explore physicalization of experiential data because it often involves an intense and memorable personal experience, and participants often collect data in the form of a GPS track.

Physicalization describes the process of creating physical visualizations of data, as well as the objects thus created. Physicalization is akin to visualization in that it attempts to make data more easily understandable and relatable to a given audience. Physicalization, however, provides *physical affordances* that allow for senses other than vision to participate in the understanding process. Physicalization also engages visual perception differently than images on a piece of paper or on a screen.

Recent work investigates how people relate to physicalizations [11–13]. Some of this work focuses on representations of population-level statistics such as GDP and employment rates for different countries [11]. Other work considers physicalization of personal exercise data [13, 14, 24] as a means of providing motivation to exercise more.

Physicalization of *experiential data*—data describing a significant personal experience—has not been studied. Interacting with physicalizations of these data may create a different kind of experience than either physicalizations of other kinds of data or other ways of interacting with experiential data.

Given a GPS track from a person's run, we create a physicalization of that track by downloading elevation data for an area containing the path. The elevation data is combined with the GPS path data to create a model of the terrain with a raised path, which is then 3D printed. A physicalization of a running path is shown in Figure 1.1.

We conducted two semi-structured interview studies designed to form and then test hypotheses related to interaction with physicalizations of trail running data. These studies focused on individuals interacting with data from their own runs. We found that physicalizations of experiential data allowed individuals to more easily connect with memories about their experiences, and that this connection elicited greater enthusiasm than on-screen or on-page visualizations.

In our interview studies, participants told significantly more stories when interacting with physicalizations than with paper maps. We hypothesized that this might have been because physicalizations made it easier to perceive characteristics of a path through mountains than a 2D topographic map would.

We tested our hypothesis by presenting 36 people with 2D paper or 3D plastic versions of the same path and terrain and asking questions about the terrain and path. People answered questions involving characteristics of *both* the path and terrain, such as "find the highest point on the path" with greater accuracy and in less time using the 3D printed model than when using a paper topographic map.

However, people could identify properties of just the path or terrain *alone* with equal accuracy and speed using paper or plastic. These include questions like "find the highest point on the terrain" or "find the straightest section of the path."

In this thesis, we will discuss related work and provide a brief overview of the process of creating these physicalizations. We will then describe each user study and its results. Finally, we will present a further discussion of our hypothesis regarding users' interactions with terrain physicalizations, and describe how we might frame those interactions within cognitive theory. We will also briefly discuss alternative hypotheses and possible future directions.

Chapter 2

Related Work

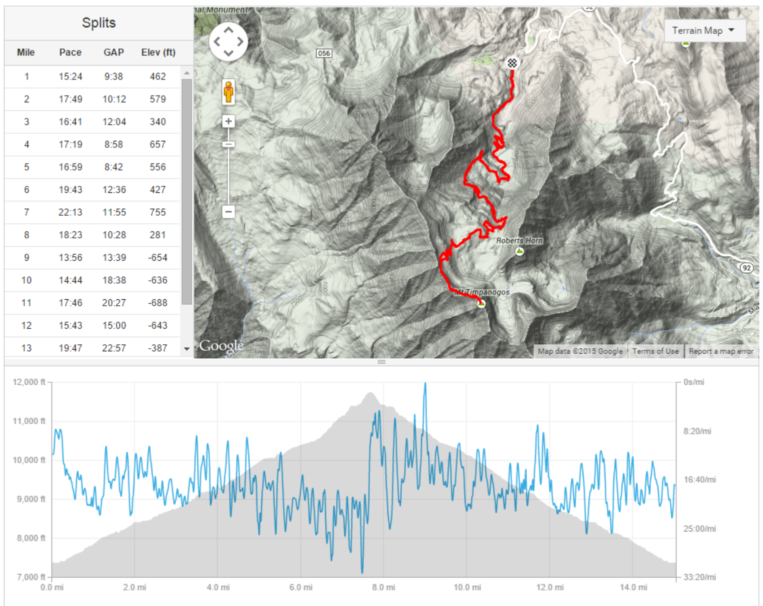


Figure 2.1: An example of a visualization of a trail run from strava.com.

2.1 Visualizations of Running Path Data

2.1.1 2D

Maps are familiar visualizations of geographic data, with topographic maps being a common visualization of terrain data. Our work essentially takes a topographic map and inflates it in 3D, replacing contour lines with physical contours. It is our belief that the physical and visual affordances this provides make this type of topographical data more approachable to the layperson, allowing them to more easily relate to and understand the shape of the terrain.

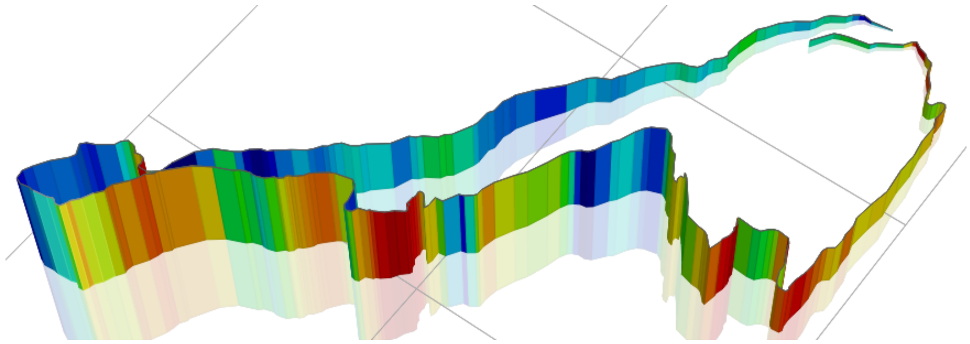


Figure 2.2: An example of a 3D path visualization from veloviewer.com.

Many on-screen 2D visualizations of running path data also exist. Most companies that provide services in support of GPS devices (Garmin, Suunto, Polar)[1] or run tracking apps for smartphones (Strava, Runkeeper, Endomondo)[2] provide some kind of on-screen map visualization. Figure 2.1 shows an on-screen representation of a run generated by Strava. This representation uses a shaded relief map and a chart of elevations to depict the topography traversed during the user's run. While differences exist between visualizations provided by each service, such as Nike+ running[3] providing a line colored by pace, they are largely the same from one to another—a map with a line indicating the user's route.

2.1.2 3D

Doarama[4] allows a user to upload a GPX file and generate a 3D visualization in the form of a fly-by video through the terrain traversed by the path. This improves on the 2D maps by adding further context to the visualization. Controls also allow the user to go forward or backward in the visualization timeline to view it from different angles. This type of visualization, however, is still not a 3D physical object. The rendered 2D view of the 3D world only allows users to view one portion of the route and topography at a time, suffers from occlusion problems, and does not provide the opportunity to either see the whole picture or to stop and reflect on details as does a physicalization.

[1] connect.garmin.com, www.movescount.com, and flow.polar.com
[2] www.strava.com, www.runkeeper.com, and www.endomondo.com
[3] www.nike.com/nikeplus
[4] www.doarama.com

Figure 2.3: A 3D print of a physicalization generated by GPXtruder.

VeloViewer[5] provides a 3rd party service for analyzing data that users have recorded and stored with Strava, including a tool that allows the user to visualize their path in 3D, as shown in Figure 2.2. This keeps the path itself in its topographical context but lacks the larger topographical context, an essential part of the runner's experience.

While these services allow people to visualize their running data in different ways, even the 3D examples remain digital and viewable only on-screen, and 2D maps are limited in their ability to quickly convey topographical data. Physicalizing running data gives it presence, weight, and allows for physical interaction. This allows for different types of engagement, understanding, remembrance, and sharing as compared to these other methods of visualization.

2.2 GPXTruder

GPXTruder[6] is an open-source project which creates 3D physicalizations after the same manner as VeloViewer. A GPX can be uploaded and then the user can download an STL for 3D printing. See Figure 2.3 for an example. While this does bring this type of visualization into the physical world, providing greater affordances for interaction and reflection, it still suffers from a lack of greater topographical context, as mentioned with VeloViewer.

[5] www.veloviewer.com
[6] http://gpxtruder.xyz/

Figure 2.4: The Great Polish Map of Scotland, an example of a very large 3D terrain model. Image credit: Wikipedia.

2.3 3D Terrain Models

The idea of making scale representations of terrain is not a new one. Many national parks and museums include them as displays to help visitors understand topographical data. The Great Polish Map of Scotland[7] (shown in Figure 2.4) is a 2 km^2 terrain model made of concrete which was completed in 1979.

While 3D objects that represent terrain have traditionally not been widely available, 3D printing technology has made noncommercial production more feasible. Several tutorials exist online[8] that give instructions on how to prepare a model of a portion of terrain for 3D printing. Such tutorials are largely step-by-step instructions for manually creating terrain models, while we automatically create the model and the path.

Companies have also emerged in this space. Creotre[9] makes relatively large terrain models, which are produced on 3D printers and subsequently processed to prepare them for installation in places similar to traditional models: museums, visitors centers, outdoor

[7]https://en.wikipedia.org/wiki/Great_Polish_Map_of_Scotland
[8]See http://www.instructables.com/id/3D-Print-Your-Trek-in-color/ for example.
[9]www.creotre.com

retailers, etc. NiceTrails[10] produces much smaller terrains, similar in size to the terrains produced for this research. They are overlaid with satellite images, and some feature a route marked with a red line.

Our work also builds 3D physical representations of running data in topographical context. However, our purpose is not to make physicalizations of running data alone, but to understand the interactive experience created by these physicalizations and to compare that to the experience of interacting with a paper map.

2.4 HCI and Exercise

The intersection of HCI and exercise is another area in which there is strong interest, and which intersects with the work were doing. Prior work focuses mainly on creating shared experiences while exercising [1, 19, 20, 30], route exploration while exercising [18, 22, 23], visualizing activity data [4], or on motivation [2, 16]. While our work does involve data gathered while running, a form of exercise, it focuses mainly on physicalizations as a way to memorialize, relate to, and share past experiences rather than on the exercise itself.

2.5 Physicalization

Our work is related to prior work in understanding how 3D models of data affect understanding that data, as well as prior work in building physical representations of personal exercise data.

2.5.1 Physical Models of Data

Prior work in physical models of data primarily involves physical representations of bar charts and other common chart types [11, 25–27]. Jansen [11] and Stusak [25] focus on evaluating how well people learn using 3D bar charts compared to virtual representations or 2D physical representations. Swaminathan [26] and Taher [27] create systems for making 3D physical bar

[10] www.nicetrails.com

charts. The system built by Taher supports interaction with the physical model by changing the bar colors and sensing touch events.

Other similar work in physicalization or interaction with physical objects includes investigating their impact on learning [21], cherished objects in the home [5, 15], and general data representations [8, 9]. Jansen [12] provides a survey of physicalization research, and Zhao [31] develops a matrix for classifying data sculptures, which applies quite readily to physicalization in general.

As with prior work, our objective is to understand new interactive experiences created by 3D printed representations of data. However, we work with high embodiment [31] representations of personal experiential data collected by the user. This creates a more personalized experience and leads to different types of responses than the lower embodiment representations of external data used in previous work.

2.5.2 Physical Models of Exercise Data

Previous research on physicalization of data from sport has focused on abstract physicalizations derived from heart rate or other activity data. This past work focused on the emotional response produced by physicalizations, and specifically on motivation to perform more activity. Exercise data is a kind of personal data. People's long-term relationship to their personal data has been explored [6, 7, 17] but not in the context of a passive physical representation of that data.

In Sweat-Atoms [13], Khot produced abstract 3D physicalizations of heart rate data recorded by users as they participated in exercise activity. In a similar paper [14], heart rate was also used to generate physicalizations, but in this case it was based on all-day (eight hours) heart rate recordings and multiple types of physicalization designs were used. In this study, participants kept a small 3D printer in their homes and printed several different artifacts representing each day's activity as recorded via heart rate data.

In both papers, Khot's findings support the idea of physicalizations being relatable and leading to reflection, sharing, and further activity. For example, a physicalization design wherein the size of a 3D printed frog model represents the amount of daily activity was highly favored by study participants because the size of the frog clearly communicated how much exercise had been done.

Khot's work focuses on symbolic representation of heart rate data recorded during physical activity. Our work focuses on indexical representations of data such as the actual path displayed in context. Our work may provide even greater relatability because of the higher embodiment provided by an indexical representation.

In Activity Sculptures [24], Stusak used data about running, including distance, pace, and elevation gain to create abstract objects for study participants. From this data, sculptures including a jar, necklace, lamp, and figure were created from pieces representing individual runs. It was found that the objects motivated runners to carry out more varied activity as they attempted to complete their sculptures or to assert control over the shape and size of the physicalizations.

Stusak also noted that the sculptures lent themselves naturally to sharing with others, even without intentionally doing so—participants found that others would see the sculptures and ask about them, facilitating sharing. Our work involves similar findings, with the added benefit that physicalizations of running paths in context concisely convey meaningful data about the journeys in real-world context, rather than being abstract representations of specific metrics.

As previously mentioned, our work focuses on physicalizations of experiential data rather than on representing data about exercise. Apart from this, the physicalizations generated for this research are high-embodiment [31] representations of the GPS data gathered by the runner paired with topographical data about the terrain in which the run took place, whereas Khot and Stusak focused on lower-embodiment physicalizations of data about effort expended in exercise.

Chapter 3

Making a Terrain Object

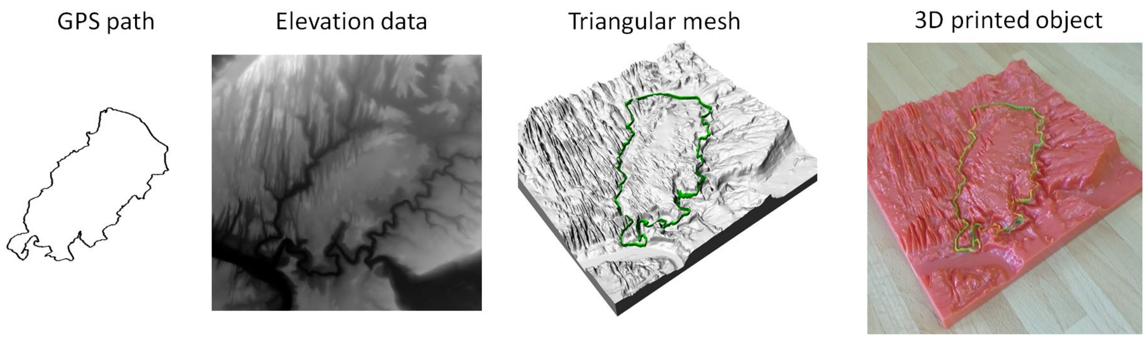


Figure 3.1: A GPS path collected by a runner is merged with elevation data to create a triangular mesh which is 3D printed.

We create a physicalization of a running path in context from a GPS track file. Figure 3.1 shows the key steps in this process. The GPS path and the elevation data are combined together to form a triangular mesh. The triangular mesh is then printed using a 3D printer with the path printed in a different color than the terrain.

3.1 GPX Files

A physicalization is generated from a path consisting of time-coded lattitude and longitude points which are stored in a GPX file. GPX, or GPS Exchange Format, is a popular and widely-adopted XML schema for recording and sharing GPS data. A path in a GPX file consists of a series of trackpoint elements, with each containing at a minimum a pair of latitude and longitude coordinates. Figure 3.2 shows a portion of a GPX file. The file in question also includes a timestamp for each element, which allows for calculation of pace.

```
<trkpt lat="41.0274810" lon="-112.2377560">
 <ele>1296.8</ele>
 <time>2016-03-19T14:59:41Z</time>
 <extensions>
  <gpxtpx:TrackPointExtension>
   <gpxtpx:atemp>14</gpxtpx:atemp>
   <gpxtpx:hr>75</gpxtpx:hr>
  </gpxtpx:TrackPointExtension>
 </extensions>
</trkpt>
```

Figure 3.2: An example of trackpoints from a GPX file. The extensions element contains extensions which are a part of this particular device's implementation but aren't native to GPX.

Other optional data such as elevation, temperature, or heart rate measurement, can be used to calculate other metrics.

3.2 Bounding Box

Before elevation data are downloaded, a bounding box must be created to determine exactly what data to download. We generate bounding boxes in a few different ways. The goal of each method is generally to produce a bounding box that nicely frames the path within its geographical context. Occasionally bounding boxes are modified by manipulating their generation parameters in order to accommodate aesthetics and include significant or interesting terrain features which are otherwise excluded.

The first, and simplest method, is to create a rectangle which is aligned with the four cardinal compass directions (north, south, east and west). In order to do this, we iterate through the trackpoints in the GPX file and determine maximum north, south, east and west extents. The bounding box defaults to 10 percent beyond these extents in each direction.

Another method also produces a rectangle, but the rectangle is aligned along the major axis of the GPX path. The major axis is found by iterating through each trackpoint and measuring the distance between it and each other trackpoint, keeping the pair of points that are the farthest from each other. A rectangle is constructed which aligns with this axis. This type of bounding box allows for the inclusion of all of the terrain necessary for the path and very little other terrain. While this method minimizes material used in producing the physicalization, it also frequently leads to less interesting and aesthetically pleasing results, since the topography in context is a central part of the physicalization.

The third method employed involves using GIS, or Geographic Information Systems. In this case, a GIS shapefile is used to create a boundary. This boundary may be from a shapefile created by a GIS professional, describing a political border or other geographic boundary, or may be simply drawn in an arbitrary shape using online tools[1]. This type of boundary works best for situations when having a non-rectangular boundary adds to the data represented in the terrain. One such example would be printing a terrain from a run that took place in a national park, where the outline of the terrain can represent the boundary of the national park.

Examples of each method can be seen in Figure 3.3. Often, the default settings produce a result which includes enough topographic context to be informative and aesthetically pleasing. When this is not the case, adjusting the defaults to include more terrain generally produces the best results. As mentioned, when a boundary adds information to the physicalization, the GIS shape method is best. In practice, the method that aligns with the major axis doesn't generally produce results which are useful, as minimizing the amount of terrain displayed tends to work counter to the goals of this research.

3.3 Data Array

A 2-dimensional array is created in which to store data representing the terrain model. Later, this array will be tessellated and capped to create a printable solid form. Data stored as points in an array are an implicit representation of the actual terrain surface. This implicit representation consumes less memory than a tessellated surface representation while still supporting the use of efficient algorithms to support operations we need to perform on the surface. This implicit representation is later converted into a tessellated representation since that is what 3D printers expect as input.

[1] http://gis.ucla.edu/apps/click2shp/

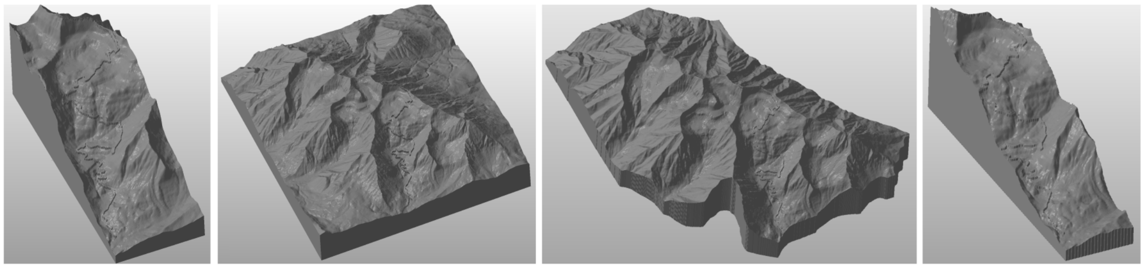


Figure 3.3: Different bounding boxes with the same route and terrain. The first is the default alignment with the default 10% padding. The second shows the default alignment with padding set for aesthetics. The third shows a bounding box set by a GIS shapefile representing the boundaries of the corresponding wilderness area. The last shows a bounding box aligned with the major axis of the route.

Downloaded elevation data will be merged into this array. The size of this array is determined by the size of the bounding box in meters and the intended resolution at which elevation data is to be downloaded. Each point in the array includes the latitude and longitude for that point, as well as the X and Y coordinates in meters relative to the southwest corner of the terrain. We default to downloading elevation data at a 10-meter spatial resolution because this is the finest resolution for which data is widely available in North America.

3.4 Downloading Elevation Data

Elevation data is next downloaded and merged into the array. The second image in Figure 3.1 is a grayscale rendering of the elevation data for the bounding box of the GPS path. Elevation data is available from a number of sources. The US Geological Survey makes digital elevation data available in several file formats and at a variety of resolutions. This data can be downloaded and then sampled via direct file access, or a GIS database such as PostGIS can be configured to serve this data.

We used the Microsoft Bing Elevations API[2] rather than manually accessing files or hosting a PostGIS server. Many web services and APIs are available for requesting elevation

[2]https://msdn.microsoft.com/en-us/library/jj158959.aspx

data. The Bing API allowed us to download up to 1024 points of elevation data at once by specifying northeast and southwest corners of a region along with the desired number of rows and columns of evenly spaced elevation points to return.

For retrieving elevation data, the array of data points is divided into tiles of 32x32 (1024) points. An API request is made for each of these tiles, and the data received is stored in the 2D array. The 2D array now contains an implicit representation of a virtual model of the terrain, with each point containing X, Y, and Z values corresponding to location and elevation in meters, along with the matching latitude and longitude values.

As is common practice in creating raised relief maps, we exaggerate the terrain in the vertical direction in order to make features more closely match perception. Our vertical exaggeration scale ranges from 1.5 to 2.5 and is set subjectively.

In bounding box generation methods where the bounding shape is irregular or is not aligned with cardinal directions, we download rectangular patches aligned with cardinal compass directions because that is the interface exposed by the web service.

The 2D array now holds the necessary data to generate a tessellated triangular mesh representing the terrain, however the mesh is not actually generated until the model file is written to disk.

3.5 Creating a Path

A raised path is created which represents the route recorded in the GPX file. This was initially attempted using constructive solid geometry (CSG) operations on an in-memory triangular mesh. This proved cumbersome and slow, as individual CSG operations involving a complex triangular mesh can be computationally expensive and accurately representing the path required many such operations.

Instead, we raise the path by finding a number of points nearest each GPS fix and raising the Z, or elevation, value of those points by a fixed amount. After experimenting with different path heights and widths, we fixed the path width and height at 1.5mm in the

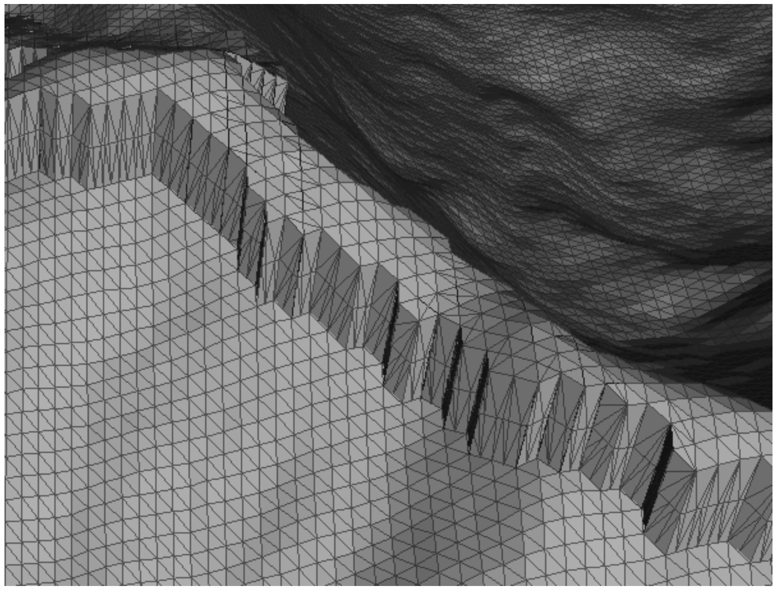


Figure 3.4: A virtual rendering depicting a small portion of terrain with the raised path.

printed models. At this size, the path is easy to see but does not appear to be a long wall running through the terrain. This size was found to be consistently usable across different sizes of terrain models. A rendered example of a portion of terrain with raised path is show in Figure 3.4.

Dimension conversion is necessary in order to raise points by the correct amount. Raised points that represent a path should be raised 1.5mm in the final 3D printed object. However, the points are actually raised in the 2D array of elevations. The values in this array represent meters of elevation in the original terrain. We compute s, a scaling factor for converting mm in the 3D printed model to meters in the original terrain, by dividing the north-south length of the terrain bounding box (in meters) by the corresponding length of the 3D printed model (in millimeters). The size of the 3D printed model is set before printing.

We then compute the path offset as $1.5s$ (s being our previously-computed scaling factor) and raise points in the terrain model by that offset. All points in the terrain model that lie within $0.75s$ meters of a GPS point in the GPX file are raised by that offset.

```
facet normal 0 0 100.100867688964
    outer loop
        vertex 1300.6387548504 280.144780423469 25.9470061344382
        vertex 1310.64366834925 280.144780423469 25.9470061344382
        vertex 1300.6387548504 290.149951152879 25.9470061344382
    endloop
endfacet
facet normal 0 -244.590181680895 0
    outer loop
        vertex 1300.6387548504 280.144780423469 1.5
        vertex 1310.64366834925 280.144780423469 25.9470061344382
        vertex 1300.6387548504 280.144780423469 25.9470061344382
    endloop
endfacet
```

Figure 3.5: An example portion of an STL file.

3.6 Mesh Generation and STL File

A triangular mesh representation of the surface is generated by iterating through the points in the 2D array, treating the values for X, Y, and Z as coordinate values for points in the mesh and generating triangles using each point and its neighboring points. The generated triangular mesh is written to a file in stereolithography (STL) format—a common format for 3D printing. An example of a portion of an STL file is shown in Figure 3.5. The triangular mesh and 3D printed object are shown on the right side of Figure 3.1.

Upon traversal of the array, the main portion of the terrain now exists as a triangular mesh in the STL file. In order to provide a terrain object with a flat bottom and sides for 3D printing, side and bottom triangular meshes are also generated and added to the STL file.

3.7 Printing the Model

The model file can now be printed on a 3D printer. We experimented with printing terrains on three different printers: a Dimension Elite fused deposition modeling (FDM) printer, an Objet30 Pro stereolithography (SLA) printer, and an Objet260 Connex3 multiple material SLA printer. Examples from each are shown in Figure 3.6.

While the FDM printer is more economical, its low vertical spatial resolution (0.178mm) creates models that appear terraced when printing terrain. Figures 3.6a, 3.6b, and 3.6c were created using this printer. Terracing is visible in the lower part of Figure 3.6a. This particular physicalization was printed with a small channel in place of the path. We then glued a red string into the channel to represent the path. This produces a path that is more visible than the single-color 3D prints in Figure 3.6, but it is difficult to encode information using the color of the path using this fabrication method.

The single color Objet30 has a finer vertical resolution (0.028mm), but paths which are the same color as the terrain tend to blend in, making them more difficult to see. The physicalization in Figure 3.6d was printed using this printer.

We used the Objet260 Connex3 because a multicolor SLA printer, even with a limited palette, can print terrains and paths in different colors, thus enhancing the path's visibility. Color can also be used to encode other information such as pace. The terrains shown in Figures 3.6e, 3.6f, and 3.6g were printed using this printer.

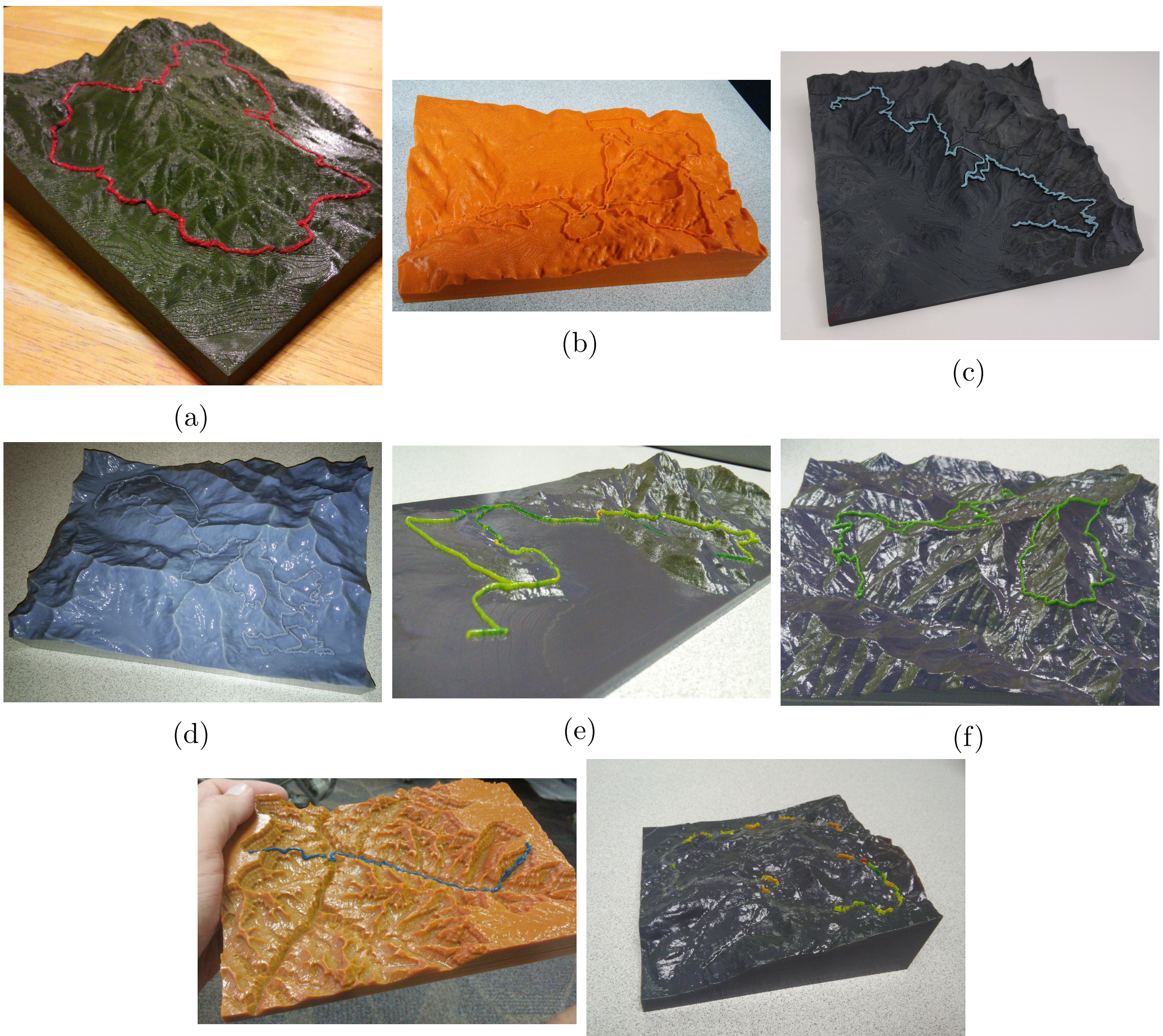
For printing models with multiple colors, the Connex3 requires a separate STL file for each material color selected. This was accomplished by generating one STL file for the terrain itself, without a raised path, and a separate file or files for the path. In cases where GPX files included timestamp data for each GPS fix, multiple path files were generated, representing different portions of the path which were discretized into buckets by pace. In the absence of timestamp data, a single path file was generated. Separate files allow for printing the terrain in one color and printing the path either in a single solid contrasting color or in multiple colors corresponding to pace. The physicalization in Figure 3.6e has pace data encoded in the color of the path, where green represents fast, yellow average, and red slow (relative to the fastest and slowest pace of the runner during this event).

The Connex3 allows for models to be printed using either a matte or a glossy finish. The glossy finish was selected as it produced better final results and necessitated less post-print clean-up of the finished model.

During the second qualitative study, we developed a fabrication method of making prints from the Dimension Elite which include a path that is a different color than the terrain.

In this process, we printed the physicalization in one color then painted the printed object with a flat black paint and painted the raised trail with a different color. Some participants who submitted GPX files lacking pacing data received prints from the Dimension that were painted, as can be seen in 3.6c. This took less time than adding the string as in Figure 3.6a and produced more aesthetically pleasing results.

Initial attempts to print models with colored paths resulted in paths that easily broke off, including portions that apparently never attached in the first place. This can be seen in Figure 3.6h. It was determined that this was due to setting the bottom of the path level with the top of the terrain. Generating the path STL file(s) so as to embed the path under the surface of the terrain resolved this issue.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 3.6: Examples of physicalizations printed on different printers. a) Dimension, with colored string inlaid for path b) Dimension with raised path c) Dimension, painted with painted path d) Objet30 Pro e) Objet260 Connex3, colorized path f) Objet260, single-color path g) Objet260, different color terrain to match actual terrain color h) Objet260, example with path that broke off

Chapter 4

First Qualitative Study: Understanding the Experience

In order to understand people's interactions with and emotional response to terrain objects, we conducted a user study involving 10 avid trail runners. Runners were recruited from personal contacts within the local running community as well as a local online running community. All 10 runners fit into Knaving's description of "advanced amateurs" [16]—"People who already run regularly and participate in races." Six participants were male and 4 were female. Experience levels varied from running races mostly less than marathon distance (26.2) to having run multiple 50 or 100 mile races.

4.1 Design

The instruction given to participants was to select a run or race that was significant or meaningful and for which they had GPS data, and to send us a GPX file from that run. Half (5) of the participants submitted GPX files from races. Of those who did not submit GPX files from races, 4 of 5 included attempts to summit a peak.

When asked to indicate why they had selected the routes they had, subjects' responses reflected interesting nuances about what made these routes significant or meaningful. P5 and P6 indicated that they had chosen their respective first trail races, with P6 indicating that although he has run the same race multiple times, his first experience there "means the most." P5 and P10 indicated the challenge level of their routes as influencing their submission. P2 submitted a GPX from her final training run prior to a major race. Although she indicated that she lacked the GPX data for the race itself, she felt that this run was more significant because it was during this run that she found the confidence to believe that she was ready for the race. P2 and P9 also indicated the personal significance of the terrain depicted in their prints, both either living or having previously lived in close proximity to the mountains in question, and P9 even having named a child after a feature in the range shown in his print.

Upon receiving GPX files from the participants, we created their terrains. Because of the varied nature of the terrain in which these runs took place, care was taken in preparing each terrain object to ensure that terrain boundaries and vertical exaggeration allowed for the terrains to be aesthetically pleasing. We then gave each participant their physicalization and conducted two interviews with each.

The first interview was given when the participant received their physicalization and was intended to assess their initial reactions to the print. The second was given 7 to 10 days later and was intended to assess their response to the physicalization after a period of time and to determine whether any of the initial response was due to the novelty effect since most participants were interacting with this type of physicalization for the first time. Interview questions are available in Appendix A.

The content of the initial interview focused on the users' initial thoughts and feelings, how the physicalization compared to other methods of visualization, and what they intended to do with the physicalization.

The second interview explored participants' impressions after interacting with the physicalization over a period of time. Participants were asked what they had done with the physicalization since receiving it. Other questions probed what impact, if any, the physicalization had over time on: participants' understanding of the actual terrain that the physicalization depicted, participants' remembrance of the event in question, the sharing of the experience with others, participants' running in general, and anything else participants felt was interesting and wanted to share.

As previously stated, the second interview was conducted in part to determine to what extent responses from the first interview were due to the novelty effect. The enthusiasm level of individual participants remained largely the same between the two interviews, leading us to conclude that there was little to no discernible novelty effect influence on the results of the initial interviews.

4.2 Results

We used open coding to identify themes in participants' interactions with the physicalizations. We identified "memories" as the central theme and identified six other related themes. The other themes were: stories, sharing, display, interactions, contextual understanding, and inspiration. We discuss each of them below and for the major themes discuss how they connect to the central theme of memories. Open coding is appropriate for this study because we did not know what to expect in participants' responses to the physicalizations of their data.

4.2.1 Memories

Memory was the core aspect identified in the first study. Participants frequently mentioned that physicalizations helped them to remember their experiences, and said things like "It brings back memories" (P6), "It takes you right back" (P9), and "It gives a stronger sense of memory than anything else" (P9). P2 stated in the second interview that having and interacting with the physicalization had actually increased her fond remembrance of the run and her fond feelings for and connection to the area in which it took place.

One particularly interesting facet of interactions with physicalizations and memories was mutually shared memories. Two of the participants noted that they had been with spouses on the runs they chose for physicalization and another had been paced by his spouse for a portion of the race depicted in his physicalization (pacing is running along with a racer in order to give encouragement and keep focus during a very long run). All of these participants said they had sat down with the physicalization and their spouses and spent time reminiscing and sharing stories of their shared experience. Two participants mentioned similar reminiscing and sharing experiences with coworkers with whom they had participated in the activities they selected. P2 described this time spent with her husband as "bonding over plastic".

4.2.2 Stories

Apart from participants mentioning specifically that the physicalizations aided in memory recall, memories were most frequently manifest through telling stories. 9 of the 10 participants shared stories during their interviews—even though we did not explicitly ask participants to share stories. Stories shared ranged from a brief recollection about their pace in a given section or the difficulty of the terrain to longer stories about their experiences, thoughts, and feelings regarding their run or race.

The sharing of stories was generally accompanied by the participants using the physicalizations as visual aids, indicating where on the trail or terrain events in the stories took place. Because some of the participants had undertaken a larger number of other runs or trips in the areas depicted by their physicalizations, stories were not limited to the route depicted, but frequently ventured into other areas of the terrain depicted.

One participant also took the time to use his phone to look up pictures from the trip depicted in the physicalization and share them as part of his storytelling.

4.2.3 Sharing

All participants initially mentioned the desire to share their physicalizations with others. In secondary interviews, all participants mentioned having shared with others, and indicated that they were able to use the physicalization as a tool in sharing.

Most frequently, participants were interested in sharing with their immediate family—spouses and children. Coworkers and friends—especially other runners—were also frequently included in sharing. P3 indicated that she had shared an image of her physicalization on social media. One participant (P9), clearly the most enthusiastic about the physicalizations, said he would like to "put it in [his] pocket" or "make a keychain of it" so he could carry it everywhere and show it to everybody.

Given that physicalizations were intended as monuments to help participants remember significant personal experiences, it naturally follows that they would want to share physicalizations and associated memories with friends and family. This is especially true if, as a participant in the second qualitative study said, they agree that "Its a much truer representation. Something I could share with my family and help them get a better sense of what I did, especially for those who don't get a terrain map."

4.2.4 Display

Every participant expressed a desire to display their physicalizations somehow. In general, participants wished to put the physicalization in a visible, prominent location. Three said that they already had a location where they displayed medals, bib numbers, and other race memorabilia, and that they would like to keep the physicalization there. Others put them in home offices, on the mantel, and even on dressers.

Three participants took theirs to work, where they displayed them. Two of them indicated that they had been "a major conversation starter" (P9). P9, whose physicalization depicted the Tetons, a rugged mountain range on the Idaho/Wyoming border in the western United States, shared that a coworker unfamiliar with such rugged mountains was "blown away" by his print.

Similar to sharing, we can reason that since runs selected by participants were chosen because they were significant and/or meaningful to them as individuals, it follows that they would want to display their physicalizations. Physicalizations, and physical objects in general when used as mementos, provide a type of ambient sharing, act as periodic reminders of happy memories and emotions, and invite physical interaction.

4.2.5 Interactions with physicalizations

Although the intent of the qualitative studies was to understand individuals' emotional responses, we also observed physical interaction with the physicalization as participants remembered the experience and what the landscaped looked like.

Upon receiving the physicalizations and without being prompted to do so, all participants began interacting with them in a physical manner. Interactions included:

- Picking up and holding physicalizations
- Viewing physicalizations from different angles
- Holding the physicalization so as to view from a very low angle, attempting to see as one would normally see from ground level
- Leaving physicalizations on the table and moving around to see them from different angles
- Tracing the route and other routes
- Pointing to indicate landmarks and interesting terrain features
- Closely inspecting the route and terrain features
- Where applicable, comparing the physicalization to the actual mountains it depicted

Such physical interactions were frequently interspersed with the sharing of memories and stories, during which more interaction, such as pointing out a specific location from the story, would take place. This seems to indicate that physical interactions had a lot to do with helping participants to connect with their memories of the experience.

Participants also indicated that others with whom they shared the physicalizations were interested in touching, holding, and physically interacting with the physicalization. In the words of P1, "people seem to love to touch it." Others who had outdoor experience in the areas depicted also often shared their stories or experiences during their interactions with the physicalizations.

4.2.6 Contextual Understanding

Participants indicated that the physicalizations helped them to "see the lay of the land" (P5) in a way that was easier to understand and more relatable than other methods of viewing, such as paper or online topographic maps. This understanding served to reinforce or to correct memories of the landscape in which the run took place.

One participant described the physicalization as helping her to understand where certain landmarks were in relation to each other and to the route she had run. Another mentioned noticing that two sections of trail that were separated by many miles in the race course were in fact quite close geographically.

Four participants also noted that others with whom they shared their physicalizations found it easier to understand their experience than with a map or without physical aids. This was especially so when sharing with those who were not as experienced in the outdoors. P8 indicated that his wife felt the physicalization made much more sense than the maps he frequently shows her in trying to explain where he is going or where he has been.

It is this aspect of the physicalizations that seems to enable individuals to connect so freely with memories and emotions. The indexical nature of the terrain physicalizations, the reduced mental effort required to understand such a representation, and the path and terrain reminding participants of their experience seems to help unlock memories.

4.2.7 Inspiration

Five participants mentioned that the physicalizations had inspired them to find new routes that they wanted to run. The two participants who were already particularly familiar with the areas depicted in their physicalizations indicated that they wished to plan new routes and run them in order to get to know these areas even more. P8 called his extended interaction with the physicalization—looking for new routes and examining the terrain involved in known routes—"exploration" and mentioned sharing his "discoveries" with others as well.

A different type of inspiration encountered was motivation provided by the physicalizations. P1 admitted to choosing his route for this purpose, it being a race that he had attempted previously but was not able to finish. He indicated that the physicalization was inspiring him in his training and that he hoped to complete the race in a year. Another said that using the physicalization as a memento for his experience had given him motivation to plan and attempt more such running adventures.

It could be that the memories brought to mind by the physicalizations, and the emotions associated with them, cause individuals to have a greater desire to plan more such experiences that build on, reinforce, and serve to create more positive memories.

Chapter 5

Second Qualitative Study: Exploring Storytelling

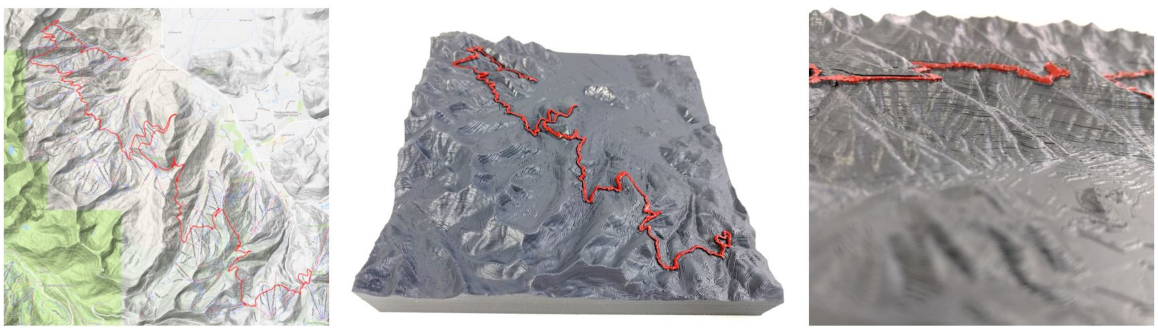


Figure 5.1: An example of a physicalization and corresponding map as used in the second qualitative study. The image on the right shows the physicalization from a low viewing angle.

The second qualitative study explored the theme of memory sharing and storytelling identified in the first study. The study had two purposes. First, to determine whether or not participants tell more stories when interacting with physicalizations of their running data compared to interacting with a printed paper map showing the same data. Second, to compare participants' reactions to physicalizations and 2D printed maps as guided by the themes identified in the first study.

5.1 Design

Participants were recruited in the same manner as the first study and were given the same instructions, however, in this study only one interview was conducted. The interview was conducted in two parts: one focusing on the physicalization and the other on a paper topographic map the participant was given which was of roughly the same area as the physicalization and included the route. See example in Figure 5.1.

During each interview we counted how many stories the participant told for each representation of the data. At the end of the interview we told participants that we were counting stories told.

Questions for each portion of the interview were identical, with the exception of the physicalization portion also including a question asking the users how the physicalization compared to viewing a topographic map. The choice to use identical questions for both representations of the data avoids introducing biases based on the content of the questions. Half of the participants were shown and asked about the paper map first and the other half saw the physicalization first. Questions are available in Appendix B.

Questions were designed to generally probe participants' feelings about each medium, for example how they felt the medium portrayed and related to their experience and whether it had any effect on their remembrance of the experience or the physical terrain in which they ran. Questions were written to explore participants' response to each without specifically prompting for stories or memories, and follow-up questions were worded to avoid specifically asking for stories or memories. In addition to counting stories, we also made notes about the participants' reactions to each data representation.

5.2 Results

Overall, there were 41 stories told with the physicalizations and 12 with the maps. This gives us a mean of 5.125 per participant with a standard deviation of 3.07 with physicalizations, and a mean of 1.5 with a standard deviation of 1.62 with maps. The difference is statistically significant ($p = 0.016$, $n = 10$ using a paired two-tailed t-test). One participant (P7-2) said "the memories are all already there, but this [the physicalization] will help keep them fresh and bring them to mind."

While response to the physicalizations in both studies was overwhelmingly positive, one participant (P3-2) in the second study did not care for the physicalization, and said he'd like to throw it away. In the case of P3-2, the very large scope of the race he had submitted led to a physicalization which was much flatter overall, with very little height contrast as compared to other physicalizations produced for the study. It could be that this participant's relatively unexciting physicalization was a special case which served to establish a lower bound for the amount of physical variation to expect in a terrain physicalization in order to make it usable and relatable. This could also be viewed as an upper bound on the amount of terrain able to be depicted in a single print.

Another participant (P2-2) actually told more stories with the paper map than the physicalization. This could be attributable to the fact that he saw and was reviewing the physicalization prior to beginning the interview, connecting him to memories that he then continued to relate as the interview progressed with the map portion first. It could also be because he already had a particular affinity for the topographic map of the race, stating that he had spent much time reviewing it both prior to his running the race as well as in the approximately two years since as he planned to return and finish the race, having had to drop out before.

Regardless of their general feeling about the paper map, users were much more interested in the physicalization. Even those who had high quality maps indicated that they preferred the physicalization as a memento and indicated that they were better able to remember their experience than with a paper map. Participant P8-2 said "its a much bigger impact than paper, you can almost look and see the view."

One participant (P5-2) is colorblind and pointed out that the physicalization is easier to read than topographic maps which can depend on color cues.

Another participant (P1-2), who told the most stories of any when interacting with the physicalization, described taking note of a physiological response to the physicalization, saying, "There's an emotional attachment here [indicates physicalization] that I don't get from this [indicates map]. My heart starts beating. I can physically feel the difference."

Chapter 6

Quantitative Study: Paper versus Plastic

Figure 6.1: The physicalization and paper map used in the quantitative study.

After the first qualitative study, we hypothesized that participants may have told stories and related memories in the first study because they could process the trail and terrain data with less effort when looking at a physicalization compared to a 2D map on paper. We designed a quantitative study to compare participants' speed and accuracy when answering questions about paths through mountainous terrain using physicalizations and 2D printed topographic representations of that data.

6.1 Design

Each participant was given a 2D paper or a 3D plastic version of the path and terrain as shown in Figure 6.1. We chose to use between-subjects control, rather than within-subjects control, to avoid a learning effect based on seeing one medium before the other. We could have used within-subjects control with two different combinations of path and terrain: one for

Table 6.1: Values on the left represent total correct responses with p-values calculated using the N-1 χ^2 test. Values on the right represent mean time-on-task with p-values calculated using between-subjects comparison t-test. Statistically significant differences are marked with an asterisk on the corresponding side.

Count of correct responses			Question	Mean time		
Phys.	Map	p-value		Phys.	Map	p-value
11	6	0.095	Highest point	12.39	20.42	0.076
18	6	7e-6	*Lowest point*	4.36	22.49	0.0008
15	15	1	Cliff	16.12	25.66	0.14
9	14	0.083	Canyon	8.34	15.77	0.11
9	7	0.50	Saddle*	9.39	18.52	0.0032
13	13	1	Ridgeline*	7.43	17.13	0.039
15	13	0.42	Bowl	7.82	21.41	0.12
14	14	1	Hilliest region*	9.04	17.23	0.022
16	13	0.21	Flattest region	10.19	10.88	0.85
13	12	0.92	Curviest part of route	16.39	17.18	0.86
17	14	0.3	Straightest part of route	8.61	9.47	0.8
18	9	0.0005	*Lowest point on route*	6.21	20.54	3.3e-5
17	2	6e-7	*Highest point on route*	3.97	16.44	0.0002
16	8	0.01	*Steepest portion of route	18.87	24.11	0.33
10	12	0.47	Flattest portion of route	12.89	11.37	0.66
15	4	0.0002	*Route crossing saddle*	11.07	27.62	0.0034
17	10	0.01	*Best view	15.59	18.07	0.47
15	13	0.4	Least visibility	11.78	18.20	0.2
18	12	0.007	*Fastest portion of route	13.33	11.17	0.602
17	15	0.29	Slowest portion of route	8.85	8.99	0.96
N/A	N/A	N/A	Total time*	247.98	380.05	0.033

the paper map and a different one for the physicalization. The difficulty arising there, which we chose to sidestep, is selecting terrains and paths with similar enough features so as to be effectively comparable in terms of the level of difficulty they presented to study participants.

An unshaded paper map was used rather than a shaded map because most paper topographic maps are unshaded. It may be that for the type of tasks we gave participants, a shaded relief map would have been easier for participants to understand. The selection of the shaded relief map in the qualitative study was based on the fact that it is the exact representation used by social media sites used by runners as a default, and that many of the trail runners we were interviewing would therefore be familiar with it.

Power analysis conducted before the study based on an N-1 χ^2 test to measure significance with $p < 0.05$ to indicate significance and a medium sized effect gave a sample size of 18 participants per medium. We chose an N-1 χ^2 test because we expected that cell counts for each response would be less than five when most participants gave the same answer to some of the questions. We used an unpaired t-test to compare mean response times.

Each participant was given a list of questions and the map or physicalization. Participants were asked to read each question out loud before answering the question by pointing at the region or point which they felt best answered the question. Questions are available in Appendix C. Video was recorded for later analysis. The goal of analysis was to measure the time-on-task and accuracy of participants' responses. We measured time-on-task from when the participant finished reading the question to when they pointed at the paper map or plastic model. This included all reasoning time and pointing responses in cases where participants indicated multiple areas or points. The amount of time between reading the question and pointing at the location serves as a rough metric for the difficulty of answering the question using the different mediums. We also noted whether or not the participant pointed at the correct location or area.

6.2 Results

We employed the N-1 χ^2 test to measure the signficance of differences between correct response rates and an unpaired t-test to measure differences between time-on-task results. Results are shown in Table 6.1. Questions for which the difference in time-on-task were statistically significant are marked with an asterisk. Those for which accuracy differences were statistically significant are shaded.

Based on the data and statistical analysis, tasks which involved reasoning about the route together with the physicalization as opposed to one or the other separately, were the ones on which users performed measurably better with the physicalization than with the map.

An interesting observation from reviewing videos of participants was that those in the map condition made heavy use of labels on the map in order to answer questions. 16 of the 18 participants in the map condition either specifically mentioned the names of locations labeled on the map when answering questions or pointed directly at the labels. This seems to indicate that, where possible, participants were more likely to base answers on map labels than interpretation of contour lines. Only five participants verbally indicated that they were reasoning about contour lines in some way when attempting to answer a question. Three made verbal mention of using printed elevation values to understand the map. This could potentially suggest that using a map without labels may produce different results. However, we chose to use a map with labels because maps typically contain textual labels.

Chapter 7

Discussion and Future Work

Participants answered questions about a path in mountainous terrain more quickly and more accurately using physicalizations of the path than a topographic map. Participants also told more stories about their experience when interacting with physicalizations of their path than when interacting with a paper map showing the same data.

One possible explanation for these results is that interactions with physicalizations generate a lower cognitive load than those with paper maps. This seems to fit with the general pattern of results in the quantitative study: questions about just the terrain or just the path did not generally show statistically significant differences in either time-on-task or accuracy, while questions where the participants had to process data about both the path and terrain together were more likely to show statistically significant differences. In the qualitative study, lower cognitive load may have allowed participants to more freely recall and share memories. Further study and specific cognitive load testing would be necessary to confirm this theory.

Preattentive processing may also explain why people interacted with physicalizations of this data differently than paper maps. Preattentive processing is "performed automatically on the entire visual field detecting basic features of objects in the display" [28, 29]. It has been shown that one feature processed preattentively is 3D depth cues [3], such as those presented by the physicalizations. This could help explain the results, and may have something to do with reduced cognitive load as discussed above, if indeed that theory is true.

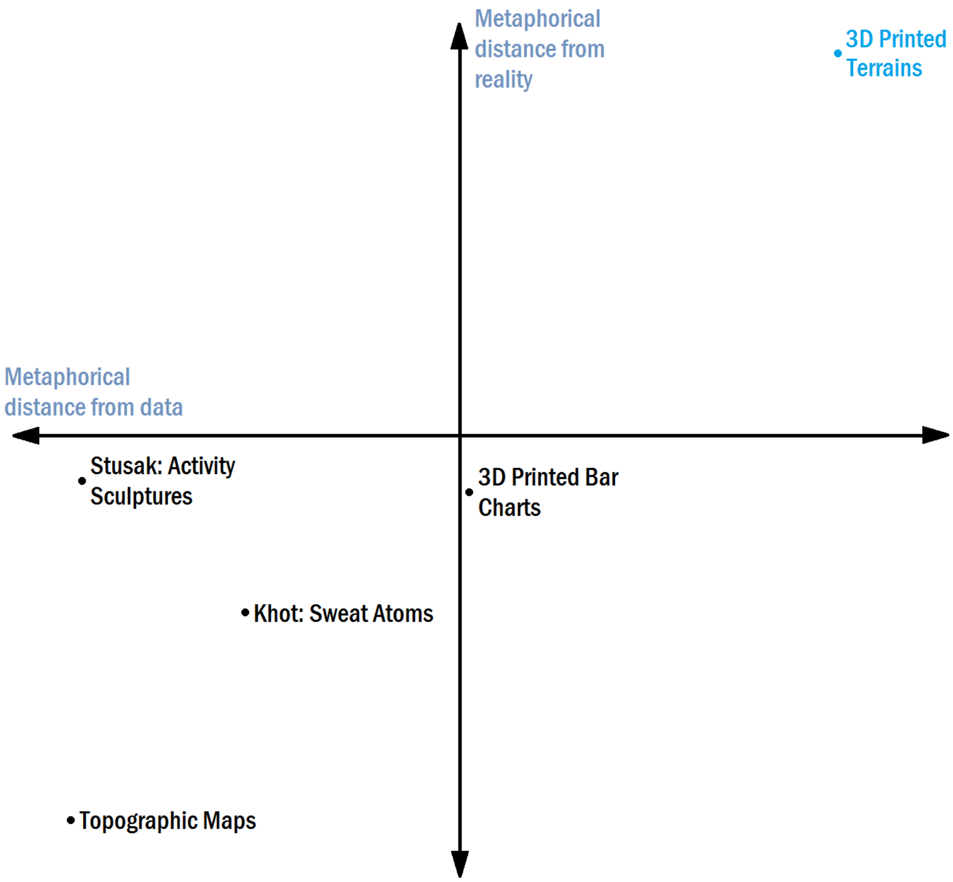


Figure 7.1: Zhao's classification matrix, plotted with projects mentioned as relating to this work.

Fitting the physicalizations into the model proposed by Zhao [31] places them at the extreme top right of the four quadrants as diagrammed in the paper (see Figure 7.1). The metaphorical distance from both data and reality in this case is quite small. In other words the *embodiment* of the physicalizations is extremely high.

Conversely, topographic maps sit at almost the exact opposite location: contour lines are a highly symbolic signifier, and do not fit any of the three criteria Zhao gives for embodiment: *single mental image*, *providing affordance*, or *intuitive*. Thus their level of embodiment is extremely low. In the language of the paper, "Embodiment has been identified as a major influential factor to a data sculptures informative value." Thus, the physicalizations—whose embodiment level is high—are much more informative to people than topographic maps—whose embodiment level is low.

As anticipated, participants and others with whom they shared the physicalizations were very interested in handling, touching, and otherwise physically interacting with them. This is an important aspect of physical objects and of physicalizations, and the heart of what differentiates physicalization from visualization. The perceptual affordances provided by physicalizations are central to this and other work exploring their utility and individuals' reactions to them.

7.1 Discussion and Observations

In the first study, the most surprising and interesting result was the extent to which the physicalizations connected participants to their memories, leading to them sharing many stories. It was this particular result that led to the development and execution of the other two studies.

Another interesting note is the way in which other people responded to the physicalizations when the participant showed the physicalization to them. On the whole, those who were more interested and/or active in the outdoors were more likely to be interested in and engage with the physicalizations when shared. This may have something to do with memories, given that participants indicated that others shared their own memories of places and experiences. Perhaps the general idea conveyed by the physicalizations of an outdoor adventure/experience helped connect others with their own memories of such experiences.

Similarly, those who were the most enthusiastic about their physicalizations were those who had spent the most overall time in the area depicted. Those who had only been there once for a particular run or race were less enthusiastic overall. This appears to stem from the memory aspect: those who had spent more time in the area depicted had many memories and stories to recall and share, while those who had only been there once did not. This reinforces the idea that memories are core to individuals' interactions with and reactions to these physicalizations.

It was unexpected that so few of the participants would express having found motivation in the physicalizations (only two actually directly mentioned motivation as a result of the physicalization). Indeed, we had initially hypothesized that interacting with physicalizations would result in increased motivation to undertake more activity. Interestingly, one participant (P6) gave what might be a possible explanation for the lack of increased motivation for the audience from which participants were gathered: "I already run a ton." This also squares with feedback from two of the other participants (P1, P10) who were less active in running at the time of interviews, and who both indicated that the physicalization had inspired and/or motivated them to train more and undertake more trail running adventures.

The phenomenon given the name "bonding over plastic" (P2) was also unanticipated, though not surprising in hindsight. It could be that the physicalizations allowed for participants and their loved ones to connect more readily with their memories and each other than they had in the past with other methods of reminiscence. It should be noted, however, that it could also be the case that physicalizations simply brought them back in remembrance of their shared experience the same as a picture or some other medium may have. Results from the second qualitative study, however, would seem to indicate that the former is true.

It is unclear whether participants' enthusiasm for sharing their physicalizations stems more from the physicalizations ability to connect people to memories and communicate more clearly, or from enthusiasm about 3D printing in general or this specific application. It is likely a mixture of the two, with individuals falling somewhere along a spectrum between them. Comments from participants in both studies would seem to indicate this, with some commenting on their desire to use the physicalizations to help friends and family understand their adventures, and others commenting on the interesting technical aspects of a 3D printed mountain.

It is highly likely, however, that participants' desire to display the physicalizations is because of the intrinsic qualities of the items themselves as physical objects, rather than any particular interest in the technical aspects of their creation. Physical objects lend themselves to display, particularly when they remind people of some important experience. It is for this reason that people have desk tchotchkes, souvenirs, and nick-knacks. This also fits in with the fact that the two most common places in which people desired to display their physicalizations were with their other running memorabilia and on their desk at work or home.

7.2 Future Work

In this work, we have explored physicalization of route and terrain data, specifically within the context of trail running. While we have focused on the topography as the interesting aspect of the physicalizations, it may be that much of the participants' reaction and memory recall has to do with *place*, rather than topography. In other words, although topography is of interest and is certainly a factor in our results, it may be that having a physicalization of the location in which the experience took place is also a factor on some level. Future work could explore this idea by creating physicalizations of other places, such as rooms, buildings, neighborhoods, campuses, and cityscapes, and attempting to understand individuals' responses to them.

Cityscapes in particular present interesting challenges and areas for exploration. While some data is available about this, in the absence of highly-detailed building model data, would the skyline still look the same? If not, would it still evoke the same response that the actual skyline might? What about other types of data that might be of interest to urban planners, such as heat flow or traffic data? Could this data be effectively represented?

While we have explored physicalizations of journeys over land, journeys over or under sea or through the air or other types of journeys, such as by automobile, present different challenges that could be explored. Physicalizations of rock-climbing routes may prove useful for both planning as well as remembrance. We have found that physicalizations of journeys over too great a distance lose some of the impact, as the terrain becomes quite flat and uninteresting. Thus physicalizing journeys by automobile could present challenges in finding a way to make them still make sense and be interesting and aesthetically pleasing. Journeys through the air or on/under sea lack the topography we've employed in framing route data. Is there a way to physicalize these journeys and still make the physicalizations understandable and useful?

It may prove interesting to follow up with participants in the qualitative studies after some period of time. Further interviews could focus on the frequency and nature of continued interaction with the physicalizations, their physical presence and role as passive reminders of participants' experience, and other aspects of participants' long-term feelings about them.

While some have explored the impact of variations in different aspects of physicalizations, such as size [10] or color, there is certainly more work that could be done in this area. This presents interesting questions in work such as ours where the embodiment level is high. It may be that exploring different applications of size, color, texture, or other physical aspects could actually lower the embodiment level. While this seems detrimental to the aims of this research, it may prove that doing so in this case would allow for encoding more data, and provide new avenues for exploration of user responses.

Our findings show that high embodiment physicalizations allow individuals to more easily understand data. This may have application in other areas, such as education, where physically representing certain concepts may help students to grasp them better. A potentially fruitful area of exploration here is physicalization of abstract concepts, in which the embodiment level may be more difficult to assess or may simply be significantly lower.

Appendices

Appendix A

Questions for First Qualitative Study

A.1 First Interview Questions

1. How do you feel about the terrain object?
   (a) Follow-up questions could relate to any of the below questions, in either section.
2. How does this compare to viewing your run on Strava/similar?
   (a) Follow-up will examine subjects experience with visualizations and how their initial feelings about the terrain differ from past experiences.
3. What do you think you'll do with it?
   (a) Follow-up might explore different ideas about using the terrain: examining, sharing, displaying, social media sharing, etc...
4. Is there anything else you'd like to share?
   (a) This question is a neutral concluding question which allows the participant to share anything else theyd like to about the experience of interacting with the terrain.

A.2 Second Interview Questions

1. After some time with the terrain, how do you feel about it now?

(a) Follow-up questions here would relate to their experience with the terrain over the intervening time and might delve into areas covered in other questions below.

2. How does your experience with the terrain compare to your initial impression/thoughts?

3. What did you do with the terrain?

   (a) Follow-up questions here would relate to what they did, and may end up centering on who they shared it with/how they shared it.

4. How did the terrain impact your remembrance of your run/race?

   (a) Follow-up questions will explore feelings and impressions generated by the terrain object.

5. How did the terrain impact your sharing of your experience with others?

   (a) Follow-up questions could revolve around the frequency of sharing, who it was shared with, and their reactions to the object, perhaps exploring how reactions to the terrain object might differ from past reactions to other forms of sharing.

6. How did the terrain impact your running in general?

   (a) Follow-up will explore whether the terrain inspired them to train more and/or harder or any other impacts it may have had on them.

7. How did the terrain impact how you think about the terrain in which the run took place?

   (a) Follow-up questions are related to further exploration/route finding undertaken by the subject, and to potential environmental stewardship inspired by the terrain object.

8. Is there anything else youd like to share?

(a) This question is a neutral concluding question which allows the participant to share anything else theyd like to about the experience of interacting with the terrain.

Appendix B

Questions for Second Qualitative Study

B.1 Questions About the Physicalization

1. How do you feel about this terrain?
2. How does this depiction relate to your actual run experience?
3. How does it compare to viewing a topographic map?
4. Does this depiction impact your memory/remembrance of the experience?
5. Does this terrain impact how you think about or remember the physical terrain in which the run took place?
6. What would you like to do with this terrain object?
7. Is there anything else youd like to share?
8. Observe and tally stories told...

B.2 Questions About the Map

1. How do you feel about this map?
2. How does this depiction relate to your actual run experience?
3. Does this map impact your memory/remembrance of the experience?
4. Does this map impact how you think about or remember the physical terrain in which the run took place?
5. What would you like to do with this map?

6. Observe and tally stories told...

Appendix C

Questions for Quantitative Study

C.1 Evaluation Questions

1. Can you identify the highest point on the terrain? Lowest?
2. Can you identify a:
   (a) cliff
   (b) canyon
   (c) saddle
   (d) ridgeline
   (e) bowl
3. Which region of the terrain is the hilliest? Flattest?
4. Can you identify the curviest section of the route? Straightest?
5. Can you identify the lowest point along the route? Highest?
6. Can you identify the steepest section of the route? Flattest?
7. Where would be the best view?
8. Where would be the least visibility (IE in a canyon)?
9. Wheres the section on which youd expect to be fastest? Slowest?
10. Where would you expect to see/where would you place aid stations for someone hiking this route?

C.2 Verbal Questions

1. On a scale of 1-10 with 10 being very confident, how confident are you about these answers?
2. Do you recognize where this is?
3. If so, how much time have you spent hiking/running/biking here?

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