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Assessing How Terrain Representations and Scale Affect the Accuracy of Distance Estimates

Kristian Mueller
University of New Mexico

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Kristian Mueller

Candidate

Geography and Environmental Studies

Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Scott Freundhschuh , Chairperson

Chris Duvall

Maria Lane

Yan Lin

ASSESSING HOW TERRAIN REPRESENTATIONS AND SCALE AFFECT THE ACCURACY OF DISTANCE ESTIMATES

BY

KRISTIAN MUELLER

B.S., Geography
B.A., Philosophy

THESIS

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Assessing How Terrain Representations and Scale Affect the Accuracy of Distance Estimates

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Kristian Mueller

B.S., Geography, University of New Mexico, 2014

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Abstract

Terrain is often displayed on maps either as background or foreground. Although terrain representations are ubiquitous, there is not a thorough understanding of map-readers' cognition of geographic surfaces from various terrain representations. The research described in this thesis empirically assessed map users' abilities at estimating straight-line distance using maps with two different types of terrain representations and at three different scales. The objective of this research was to assess how accurately map users estimate distance on the ground taking into account variations in elevation. Participant data in the form of demographics and distance estimates were statistically analyzed to determine if terrain representation and scale had a measurable and significant affect on distance estimates.

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Introduction and Background

Ancient, medieval, and renaissance maps depicted mountainous terrain as simple hill-like icons (Imhof, 2007; Raisz, 1948). Around the beginning of the 18th century a new, more scientifically communicable cartographic representation of terrain called hachures began to be employed (Imhof, 2007; Raisz, 1948). Hachures depict numerous lines to show directions slopes are oriented, which forms an overall image of slopes and terrain. Hachures can also be thought of as signifying which directions water would flow downhill, again signifying slope orientation as well as steepness (Raisz, 1948). Contours were first used in the mid eighteenth century (Imhof, 2007; Raisz, 1948) and have developed into a widespread and conventional type of terrain representation used to this day. The effect of hillshade can provide dramatic and pictorial representations of terrain which arguably visually resemble what they represent, meaning hillshade is less arbitrary than other cartographic conventions. Relief shading began development in the mid 19th century, becoming increasingly more utilized in the early 20th century (Imhof, 2007; Raisz, 1948; Robinson, 1969). In *Elements of Cartography* (1969), Robinson discusses the decades long problems of terrain cartography that began after contours and hillshade had been adequately established and utilized, and how multiple representations could possibly be combined to achieve both an aesthetically pictorial appearance and metric commensurability all at once.

> For many years to come the representation of the land form on maps will be an interesting and challenging problem, since it is unlikely that convention, tradition, or the paralysis of standardization will take any great hold on this aspect of cartographic symbolization. This will probably be particularly true of terrain representation on special-purpose and thematic maps; each such an attempt will be a new challenge, since in each case it must be fitted to the special, overall objective of the map. (Robinson, 1969, page 173).

His critique of, and concern for, cartographic problems attemptedly solved by standardization and convention are discussed in his book *The Look of Maps* (1952) and is a subject I critique and discuss below with a synthetic approach using both standardization and audience.

More recently, GIS (geographic information systems) have enabled fast computer automation and analysis of large amounts of data for representing spatial terrain data in various ways (Dent, 1999; Li et al., 2005; Crampton, 2010; Tyner, 2010; Chang, 2015). From a DEM (digital elevation model, typically synonymous with DTM (Digital Terrain Model)), contours can be derived or interpolated. Hillshade can be incorporated as well from a DEM with a specified direction a light source comes from, showing illumination and creating shaded areas (Biland & Çöltekin, 2017; Collier et al. 2003; Eynard & Jenny, 2016; Field, 2015; Huffman & Patterson, 2013; Leonowicz et al. 2010; Patterson, 2002; Patterson, 2013; Patterson, 2015; Pingel & Clarke, 2014; Veronesi & Hurni, 2014; Wheate, 1996). Hillshade images can be edited with graphics software such as Adobe Illustrator, Adobe Photoshop, and Terrain Sculptor (Leonowicz et al. 2010; Patterson 2015).

Literature Review Part I

History of Terrain Cartography

The literature review here pertaining to the history of terrain cartography draws heavily from cartography textbooks spanning from the mid to late 20th century to investigate educational and professional approaches to developing and establishing cartographic norms. Reviewed are the early authoritative textbooks of Edwin Raisz and Arthur Robinson, to Eduard Imhof's mid-century textbook solely about terrain cartography, to Judith Tyner's later 20th century textbook, with a brief discussion of Cynthia Brewer's *Designing Better Maps* from the early 2000's regarding map design in general. Imhof's *Kartographische Geländedarstellung* (*Cartographic Relief Presentation*) was originally published in 1965 for German readers as a training and instruction manual on terrain cartography. An English translation was first published in 1982 and republished by ESRI Press in 2007. Raisz's text *General Cartography* was virtually the only academic textbook in use from the publishing of the first edition in 1938 until the publication of Robinson's *Elements of Cartography* beginning in 1953 (Tyner, 2005). *Elements of Cartography* went through six editions until 1995 as *the* authoritative text on cartography, with some competition from Borden Dent's *Thematic Cartography* beginning in 1985 (Tyner, 2005).

Iconic Hills

Rows of bumps, hill-resembling icons, or as Imhof calls them, "molehills," have been used to show approximate locations of mountainous or changing terrain but were not proportionally accurate or metrically useable (Imhof 2007; Raisz, 1948). Oftentimes they were only iconic and not even pictorial. Mountains in this iconic form are found on a map from Mesopotamia dating to 2400-2200 BCE, and this graphic form was revived and experimented with during the renaissance, then began to decline in the late 18th century (Imhof, 2007). By the 16th century iconic terrain became more nuanced and more pictorial with hill icons varying in size showing relative difference in height, and sometimes employing shading. Today iconic terrain maps are still used in popular medieval and fantasy genre medias, such as Lord of the Rings movies or knight-themed video games.

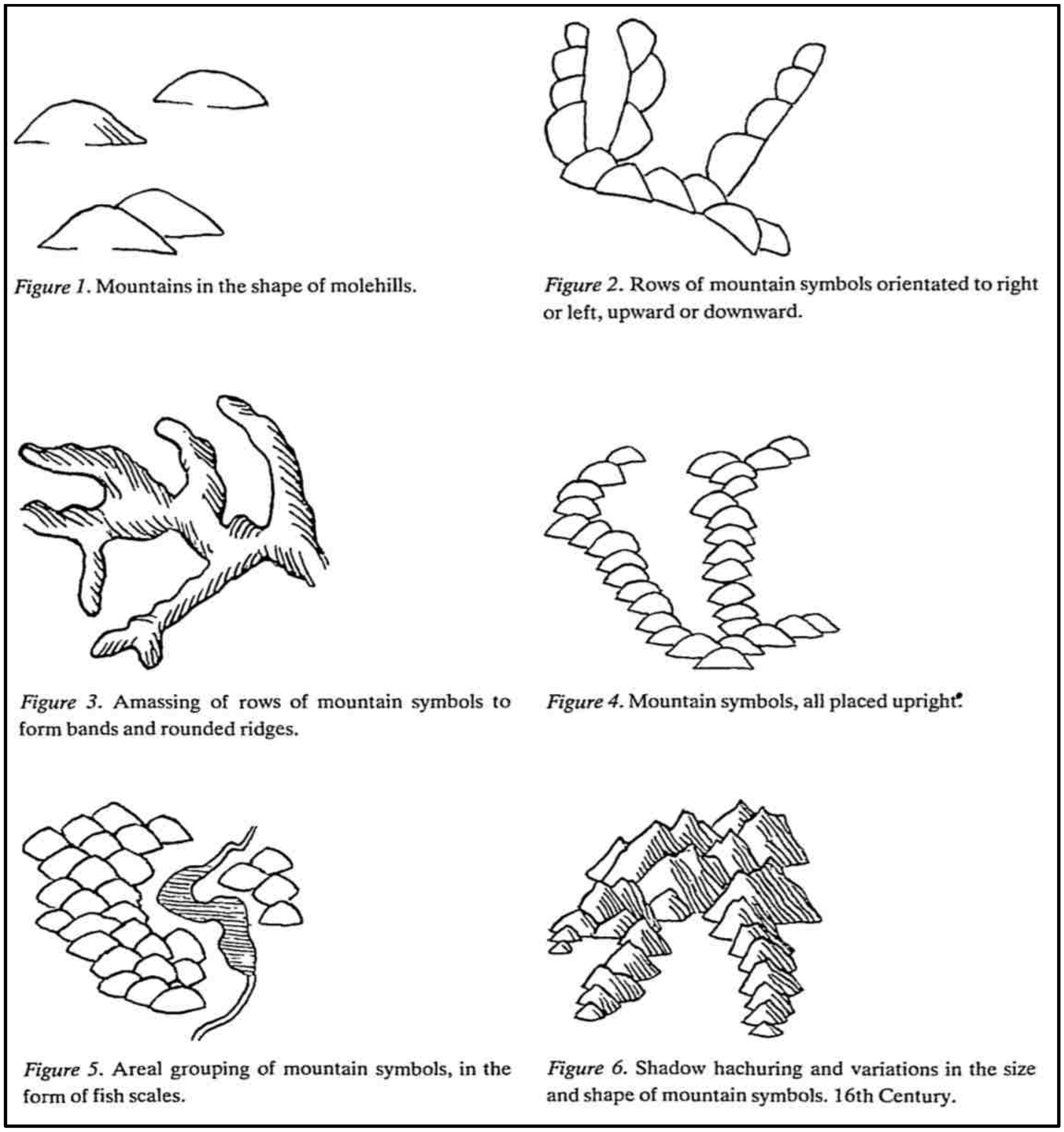


Figure 1. Mountains in the shape of molehills.

Figure 2. Rows of mountain symbols orientated to right or left, upward or downward.

Figure 3. Amassing of rows of mountain symbols to form bands and rounded ridges.

Figure 4. Mountain symbols, all placed upright.

Figure 5. Areal grouping of mountain symbols, in the form of fish scales.

Figure 6. Shadow hachuring and variations in the size and shape of mountain symbols. 16th Century.

Figure 1. Various types of “molehills” (Imhoff, 2007, page 2)

Fig. 110 Landform maps are easy to visualize.

Figure 2. Landform map of China showing terrain in iconic form. (Raisz, 1948, page 119)

Hachures

Hachures were, “a method of hill shading by closely set parallel lines” (Raisz, 1948, p. 103) in which each line indicated the slope and direction of the terrain and the directions that water would flow downward. Robinson attributes the creation of hachures to an Austrian army officer named Lehmann in 1799 (Robinson, 1969). Hachures were useful for showing relatively flat areas and moderate slopes, but were often visually crowded with lines too close together when displaying very steep slopes. A major drawback was that hachures didn’t show constant elevation metrics throughout their depictions but only sporadically with spot heights. The hachuring method was acceptable for depicting terrain at large scales, but “not well adapted to small-scale maps” in which the terrain seemed to turn into hairy caterpillars (Raisz, 1948, p. 104). Some maps combined hachures with shading (see figure 5). Raisz, Robinson, and Imhof corroborate on the historical decline of hachures beginning in the early 20th century due to the increasing use and application of contours and shading.

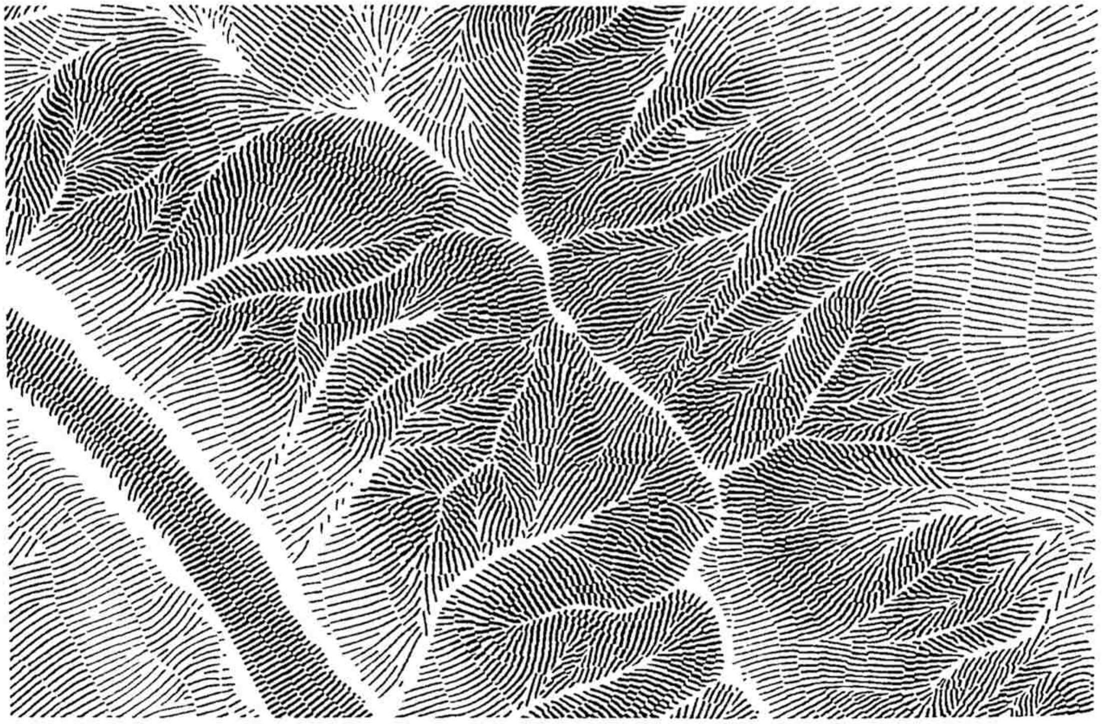


Figure 149. Slope hachuring. Üetliberg near Zürich. Scale 1:50,000, enlarged to 1:25,000.

Figure 3. Hachures at a relatively large scale. (Imhof, 2007, page 222)

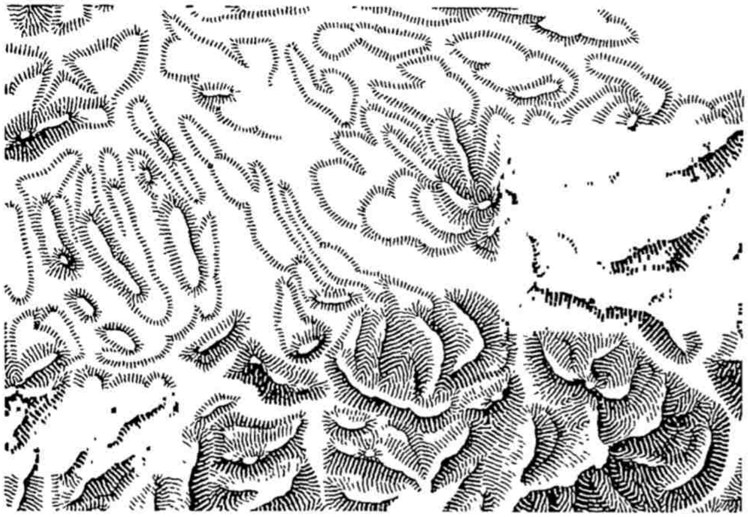


Figure 153. General mountain hachuring, scale 1:2,500,000 enlarged to 1: 1,250,000. Area: North-east Switzerland. Taken from a recent general atlas.

Figure 4. Hachures at a relatively small scale. (Imhof, 2007, page 227)

Fig. 91 Hachuring with oblique illumination is effective in mountainous country. (*From the Dufour map of Switzerland.*)

Figure 5. Hachures with shading (Raisz, 1948, page 104)

Contours

In the early 20th century, photogrammetric methods utilizing aerial photos made contours more widespread (Imhof, 2007; Tyner, 1991). Raisz defines contours as “lines that at certain even intervals connect points of equal elevation.” (Raisz, 1948, p. 106). Contours were first developed and employed by a Dutch engineer named N. Cruquis circa 1729 for navigational purposes to display the underwater terrain of the Merwede River in The Netherlands (Raisz, 1948). Eventually contours were used to depict terrain above water features, and some design conventionalities and practices were formed by European cartographers. With a datum based on sea level as 0 in elevation, contour lines were typically brown in color and had an interval of 20 feet on large to medium scale maps, such as those at a 1:62,500 scale, or 50 feet intervals for steep areas in 1:62,500 maps, and 50 foot intervals at small scale maps such as those at the 1:125,000 scale (Raisz, 1948). Another conventionality was that of a “pivot pen” or “index contour” in which every fifth or tenth contour line is thicker than the others, assumedly rendering the terrain easier to read by these markings (Raisz, 1948; Imhof, 2007). An explicit design principle stated by Raisz is, “contour lines should be labeled frequently with figures of elevation, which, if possible, should be placed on the southern slopes so as to read upward. To facilitate finding them, they are placed, if possible, in a row one above another” (Raisz, 1948, p. 109). Raisz argues that contours are superior over hachures for reading terrain and elevation changes because, “within the limits of the contour interval the height of every point can be read directly form the map, and the angle of slope can easily be determined.” (Raisz, 1948, p. 106).

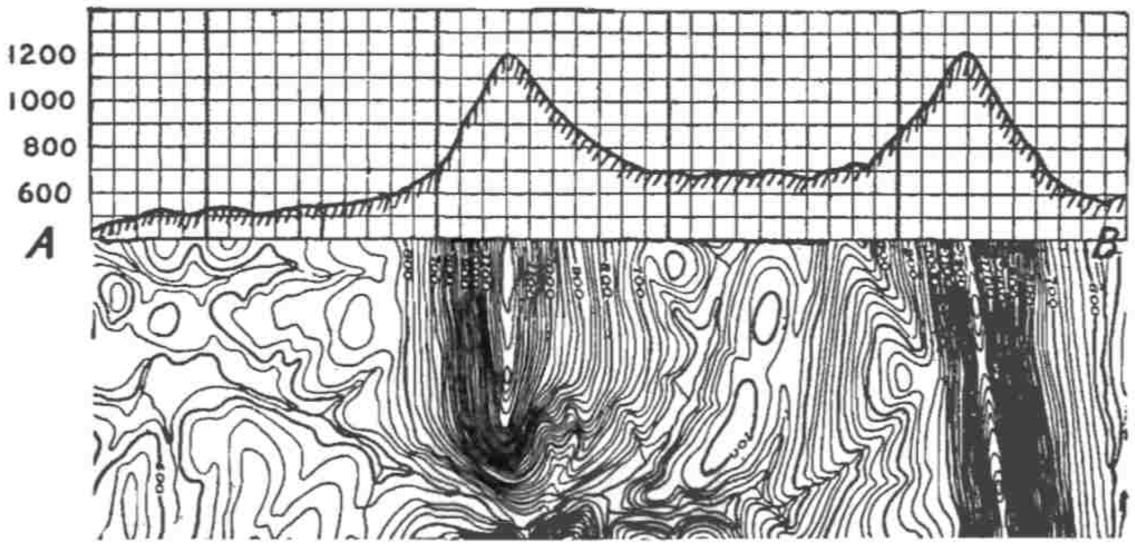


Fig. 98 Construction of profile along the line *A-B*.

Figure 6. Conventional contours with an elevation profile. (Raisz, 1948, page 110)

Robinson thought that contours were the optimum method for representing terrain due to their commensurability, even though they lacked a visual effectiveness, a characteristic that hillshade conveys and retains:

> Although contours do not present quite so clear a visual picture of the surface as does shading, the immense amount of information that may be obtained by careful and experienced interpretation makes the contour by far the most useful device for presenting the land on topographic maps. (Robinson, 1969, page 179)

Robinson provided some methodological design principles on contours when he said, “Contours on a topographic map are remarkably expressive symbols if they have been correctly located and if the interval between them is relatively small” (Robinson, 1969, p. 178) and he warns of the peril of topographic generalization of surfaces by contours when noting that, “…small hills, escarpments, and depressions can all be “lost” in between the contours. The larger the interval the more serious this possibility becomes” (Robinson, 1969, p. 178).

Tyner is in agreement with Robinson on the legibility of contours with training when she stated that, “For a beginning map reader, contour lines are not pictorial. For those who have much practice reading such maps, the contours almost appear to produce a three-dimensional effect; but this is a result of experience, not an inherent pictorial quality of the symbol. It takes training and practice to learn to read contour lines” (Tyner, 1991, p. 199).

Tyner reiterates Robinson’s concern for topographic generalization when she stated that, “Scale is also important in selecting an interval because the smaller the map scale is the more generalized the map and, by extension, the contour lines” (Tyner, 1991, p. 200) and provides examples of how contour intervals differ depending on terrain by saying, “In very steep terrain a larger interval is used than in flat terrain. 1:24,000 U.S. Geological Survey quadrangles of the Rocky Mountains may have an interval of 40 feet, while maps [at the same scale of 1:24,000] of coastal areas in Florida might have an interval of only 5 feet" (Tyner, 1991, p. 200).

Imhof addresses generalization of contours when stating, "…There are no contour representations existing at small scales that are not generalized. None can exist" (Imhof, 2007, p. 127). He explains that this is due to the accuracy at which surveying is done to obtain contour intervals used in large scale maps, which are then used to generalize contours at small scales. Although contours on small scale maps are generalized, they are accurate because of the precise large scale source.

To Imhof, the contour was, "…the most important element in the cartographic representation of the terrain and the only one that determines relief forms geometrically" (Imhof, 2007, p. 112). Imhof layed out many prescriptions for contours, such as:

> A good selection of contour intervals is very important. The choice is often difficult to make, however, since it depends not only on scale and line thickness, but even more especially on the type of terrain… In general, the smallest possible contour interval is selected, as this leads to a more accurate and more richly detailed reproduction of the shape and a more three-dimensional image. On the other hand, the smaller the contour interval, the more crowded and difficult the map is to read. Thus it is necessary to weigh the advantages and disadvantages carefully against one another. The contour interval values should be simple numbers, easily added and easily divisible. They should also produce simple numerical values when grouped in fours or fives (index contours). (Imhof, 2007, page 113)

Imhof disagrees with Raisz's design principle that contour labels should be placed in a row above each other, viewing it as too cluttered with labels in a ladder formation. Instead he prescribes that labels should generally be displayed throughout the image to read elevation values throughout the area (figure 7).

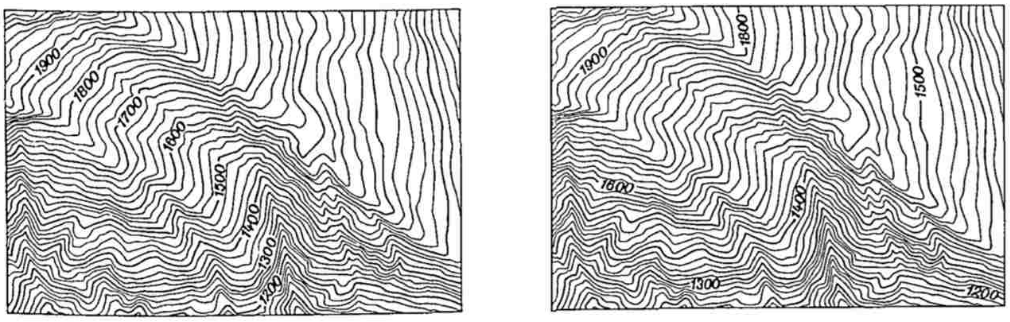


Figure 94. Poor arrangement of contour height numbers.

Figure 95. Good arrangement of contour height numbers.

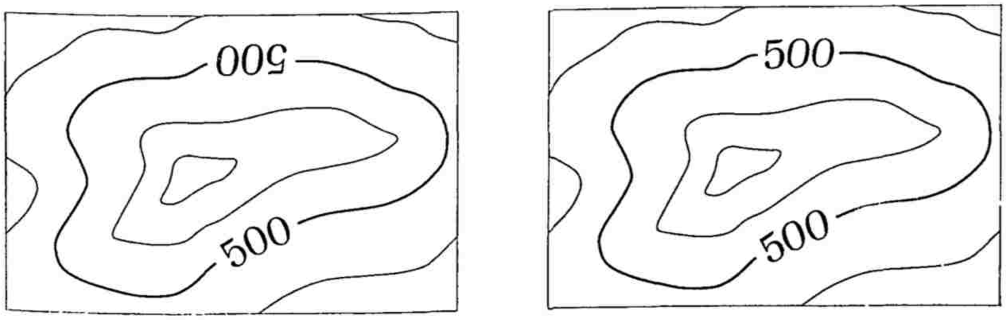


Figure 96. Numbers oriented to direction of slope.

Figure 97. Numbers with upright orientation.

Figure 7. Contour labeling (Imhof, 2007, page 139)

Among contour types there are equal interval (contours with equal distance between line) and intermediate (contours with two or more intervals, depending on slope). Imhof generally prescribed equal interval contours to be used, with intermediate contours occasionally being suitable only on large scale maps to for trained map readers with specific objectives such as engineering or land use (Imhof, 2007). To general audiences the nuance of two contour intervals is lost on average map readers, therefore intermediate contours should typically not be used (see figure 8).

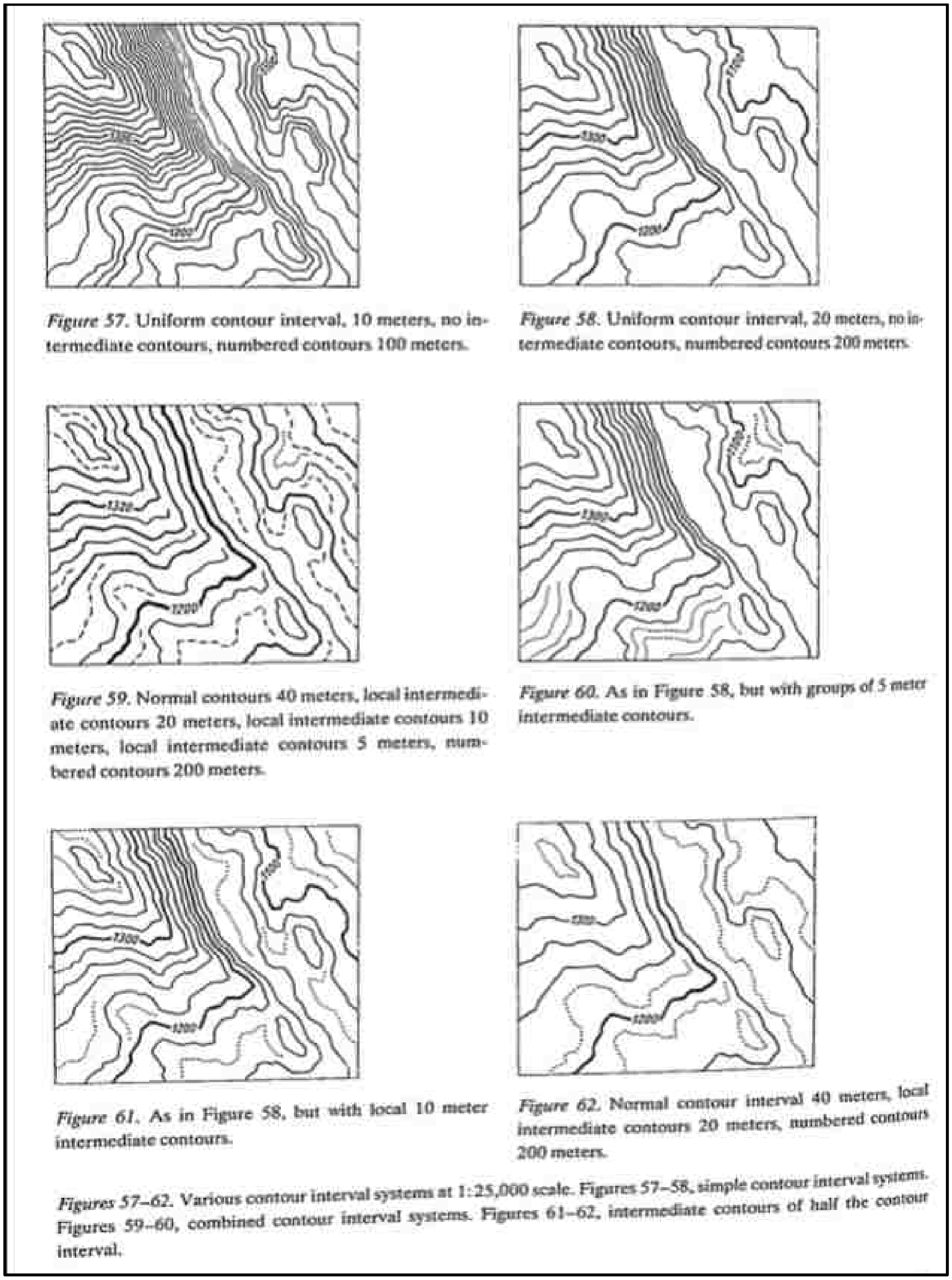


Figure 57. Uniform contour interval, 10 meters, no intermediate contours, numbered contours 100 meters.

Figure 58. Uniform contour interval, 20 meters, no intermediate contours, numbered contours 200 meters.

Figure 59. Normal contours 40 meters, local intermediate contours 20 meters, local intermediate contours 10 meters, local intermediate contours 5 meters, numbered contours 200 meters.

Figure 60. As in Figure 58, but with groups of 5 meter intermediate contours.

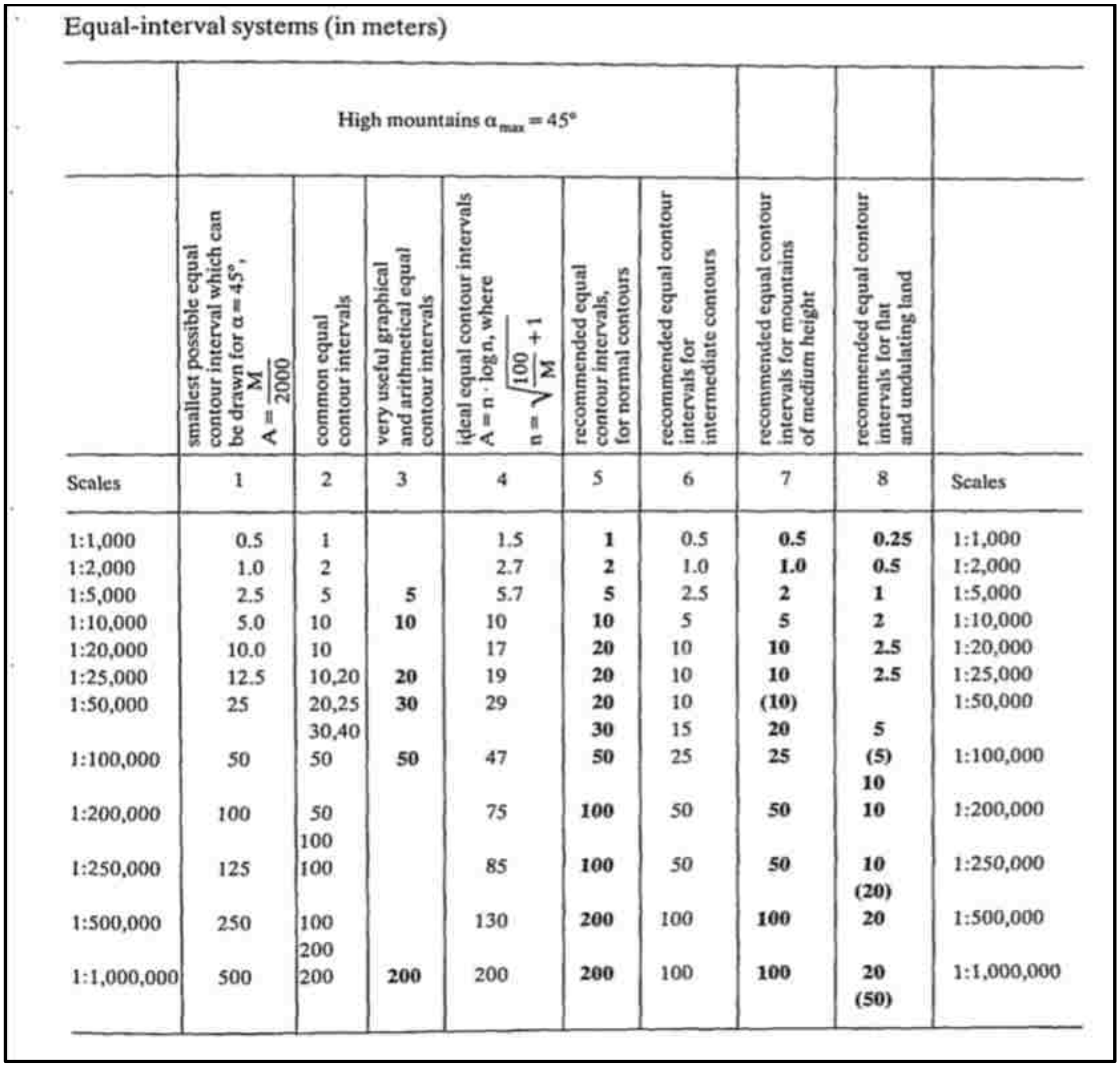
Figure 61. As in Figure 58, but with local 10 meter intermediate contours.

Figure 62. Normal contour interval 40 meters, local intermediate contours 20 meters, numbered contours 200 meters.

Figures 57–62. Various contour interval systems at 1:25,000 scale. Figures 57–58, simple contour interval systems. Figures 59–60, combined contour interval systems. Figures 61–62, intermediate contours of half the contour interval.

Figure 8. Examples of equal and intermediate contours covering the same area (Imhof, 2007, page 124)

Imhof has several mathematical formulas for producing contours depending on interval, scale, and slope. While these formulas are mathematically tenable and interesting, they would be of even more interest if their efficacy were tested by map users attempting spatial tasks to investigate if they are useful beyond professional cartographic opinion. Below is a table summarizing his prescriptions for equal interval contours (figure 9).



Equal-interval systems (in meters)

	High mountains $\alpha_{max} = 45°$								
	smallest possible equal contour interval which can be drawn for $\alpha = 45°$, $A = \frac{M}{2000}$	common equal contour intervals	very useful graphical and arithmetical equal contour intervals	ideal equal contour intervals $A = n \cdot \log n$, where $n = \sqrt{\frac{100}{M}} + 1$	recommended equal contour intervals, for normal contours	recommended equal contour intervals for intermediate contours	recommended equal contour intervals for mountains of medium height	recommended equal contour intervals for flat and undulating land	
Scales	1	2	3	4	5	6	7	8	Scales
1:1,000	0.5	1		1.5	**1**	0.5	**0.5**	**0.25**	1:1,000
1:2,000	1.0	2		2.7	**2**	1.0	**1.0**	**0.5**	1:2,000
1:5,000	2.5	5	**5**	5.7	**5**	2.5	**2**	**1**	1:5,000
1:10,000	5.0	10	**10**	10	**10**	5	**5**	**2**	1:10,000
1:20,000	10.0	10		17	**20**	10	**10**	**2.5**	1:20,000
1:25,000	12.5	10,20	**20**	19	**20**	10	**10**	**2.5**	1:25,000
1:50,000	25	20,25	**30**	29	**20**	10	**(10)**		1:50,000
		30,40			**30**	15	**20**	**5**	
1:100,000	50	50	**50**	47	**50**	25	**25**	**(5)**	1:100,000
								10	
1:200,000	100	50		75	**100**	50	**50**	**10**	1:200,000
		100							
1:250,000	125	100		85	**100**	50	**50**	**10**	1:250,000
								(20)	
1:500,000	250	100		130	**200**	100	**100**	**20**	1:500,000
		200							
1:1,000,000	500	200	**200**	200	**200**	100	**100**	**20**	1:1,000,000
								(50)	

Figure 9. Imhof’s table of metric equal-interval systems (Imhof, 2007, page 115)

Hillshade

Hillshade effect was first used in the mid 19th century, and became widely used in the early 20th century (Imhof, 2007; Raisz, 1948; Robinson, 1969,). It was produced by hand or by illuminating models and photographing them (Imhof, 2007). Shading provides a seemingly realistic three dimensional perspective, but lacks elevation metrics. Tyner reviews hillshade and stated that, "When used alone, the technique is not commensurable, but it is planimetrically correct and pictorial" (Tyner, 1991, p. 202). Imhof reiterates the conflict of hillshade's considerable pictorialness and lack of commensurability in relation to contours when he said, "In contrast to contours, shading and shadow tones can never express the forms of features with metric accuracy, since they possess only visual character," and, "shading variations never provide information of definite elevation values but rather the approximate appearance of differences in relative elevation" (Imhof, 2007, p. 188). Unlike contours which must be carefully considered in terms of their intervals at all scales, "Shading can be very effective at any scale" (Robinson, 1969, p. 176).

Throughout the 20th century there were considerations and debates about whether illumination for hillshade effect should come from the west/northwest because of a somewhat established conventionality, or from the south/southwest (Imhof, 2007; Raisz, 1948). In the northern hemisphere, where most, or all, European and scientific cartographers originated and practiced from, the sun shone from the south, therefore some argued that illumination should come from the south because of its natural imitation and it would be recognizable and useful for navigation (Imhof, 2007; Raisz, 1948). However, southern illumination flips the perspective of mountains and valleys, i.e. mountains appears valleys and valleys appear as mountains (Imhof, 2007; Raisz, 1948). The problem of the optimum direction of illumination has been very persuasively solved, or at least addressed, by Biland's and Çöltekin's (2016) empirical experiment which is discussed later. Imhof makes an interesting case that illumination from the west/northwest is possibly a norm because western cultures read and write from left to right, therefore people intuitively understand illumination from the left (west) and shading to the right (east) in maps normally oriented with north as upwards. After giving consideration to arguments for various illumination points, Imhof is partial to illumination from the west, especially for northern latitudes (Imhof, 2007).

Combinations of Contours and Hillshade

Following the decline of hachures and the rise of pictorial hillshade and commensurable contours, combinations of terrain representations were experimented with to produce satisfying and useful aggregates of cartographic terrain representations.

In *Elements of Cartography*, Robinson's main discussion and critique of terrain representation is about how different methods of representing terrain have different degrees of commensurability and visual effectiveness. Commenting on hillshade and contours, Robinson summarized the issue when he said, "The major problem arises from the fact that, generally speaking, the most effective visual technique is the least commensurable, whereas the most commensurable is the least effective visually." (Robinson, 1969, p. 173).

The USGS (United States Geological Survey) began experimenting with combinations of contours and hillshade in the 1940's (Raisz, 1948; Robinson, 1969). Raisz mentions combinations of terrain representations and says, "The most common combination of relief methods is contour lines with oblique plastic shading. Various European surveys use them, notably the 1:50,000 French maps," and, "Contour lines give exact information about slope and elevation; hachuring and plastic shading bring out visibly the forms of mountains" (Raisz, 1948, p. 118).

Combinations of hillshade and contours were argued by Robinson as the most effective and comprehensive method to represent terrain. In talking about possible methods which successfully utilize commensurability and visual efficacy he said, "The newer, shaded relief, contour maps of the United States Geological

Survey are a case in point" (Robinson, 1969, p. 173), and that this style of maps "are the most effective yet produced." (Robinson, 1969, p. 176). Tyner also discusses how the USGS began combining contours with hillshade stating, "Selected U.S. Geological Survey topographic quadrangles since the 1950's have had shading added to the contour base, which provides a highly pictorial appearance" (Tyner, 1991, p. 202).

Imhof does not mention the USGS but he does discuss the combination of contours and hillshade. He contended that, "In the depiction of forms this method of surface tone gradation is far superior to the network of contour lines, as it can reveal individual shapes and the complete form at one and the same time. Shading and shadow tones, therefore, are effective additions to contours in many maps, transforming the metric framework into a continuous surface." (Imhof, 2007, p. 159) Imhof shared the idea of the optimal terrain representation with Robinson, but with an additional feature, by thinking that the combination of contours, hillshade, and rock portrayals are the "ideal landscape relief map" (Imhof, 2007). Contours, hillshade, and rock portrayal combinations have become a Swiss cartographic convention at large scales employed by Swisstopo, the Swiss federal equivalent of the USGS (https://www.swisstopo.admin.ch/). The combination of contours and hillshade has been established as a cartographic norm for terrain being employed by the USGS for decades, and more recently by newer mapping authorities, such as Google with the terrain option in Google Maps.

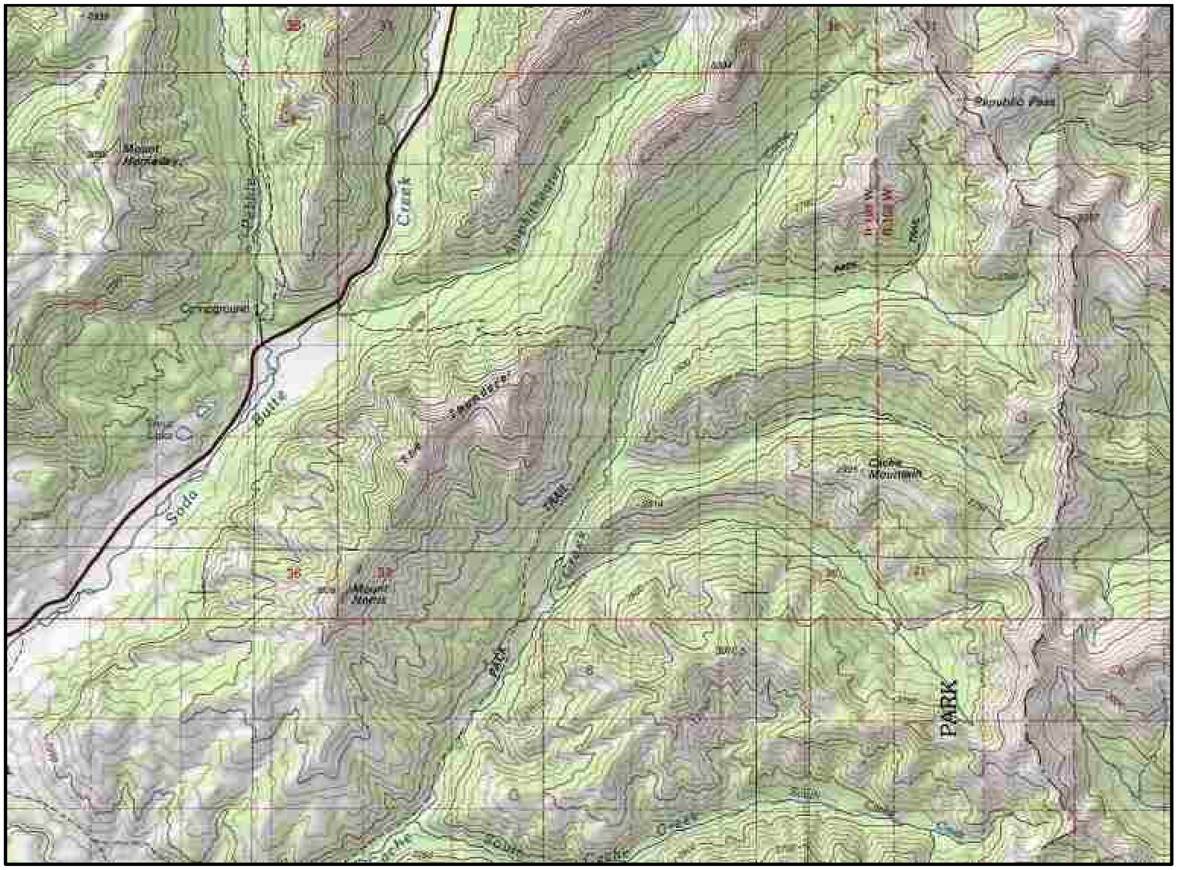


Figure 10. Portion of a USGS map composed of contours and hillshade. (screenshot taken by the author from ArcGIS Online basemap).

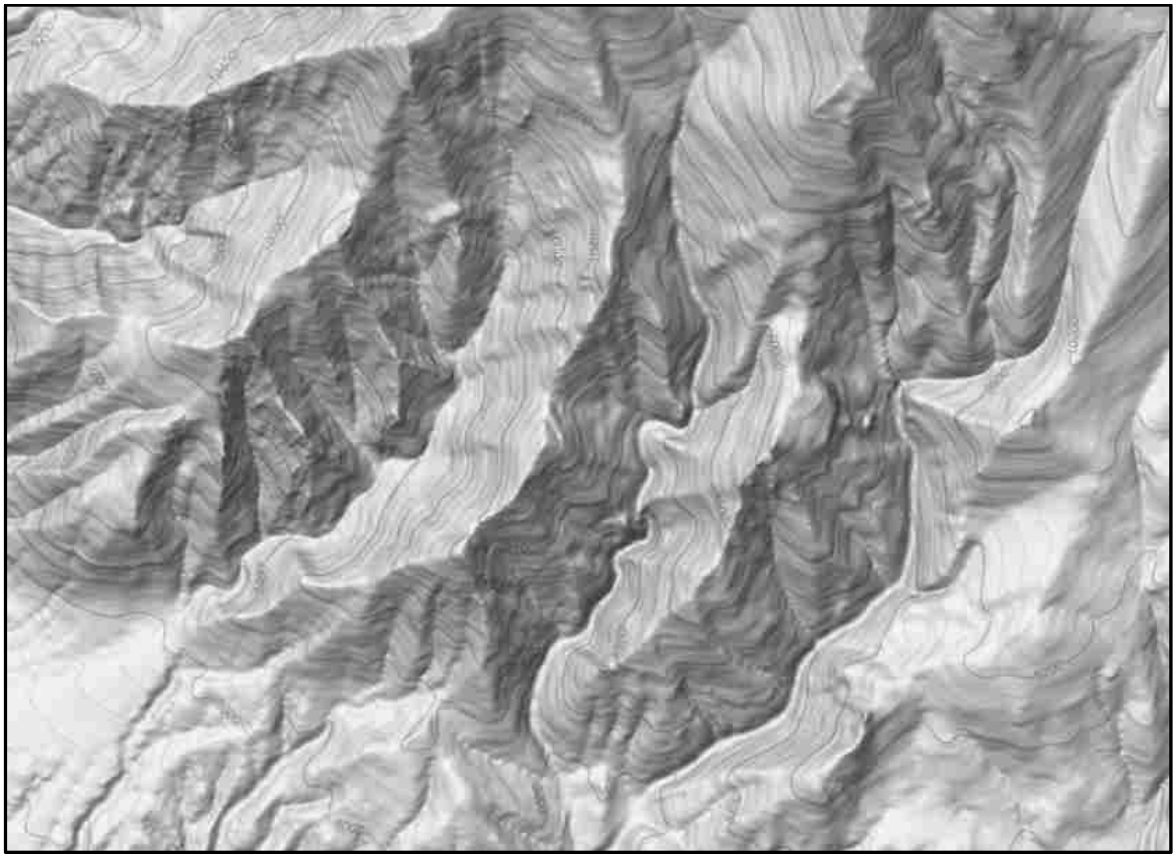


Figure 11. Portion of Google Maps “Terrain” layer composed of contours and hillshade. (screenshot taken by the author from online viewing Google Maps)

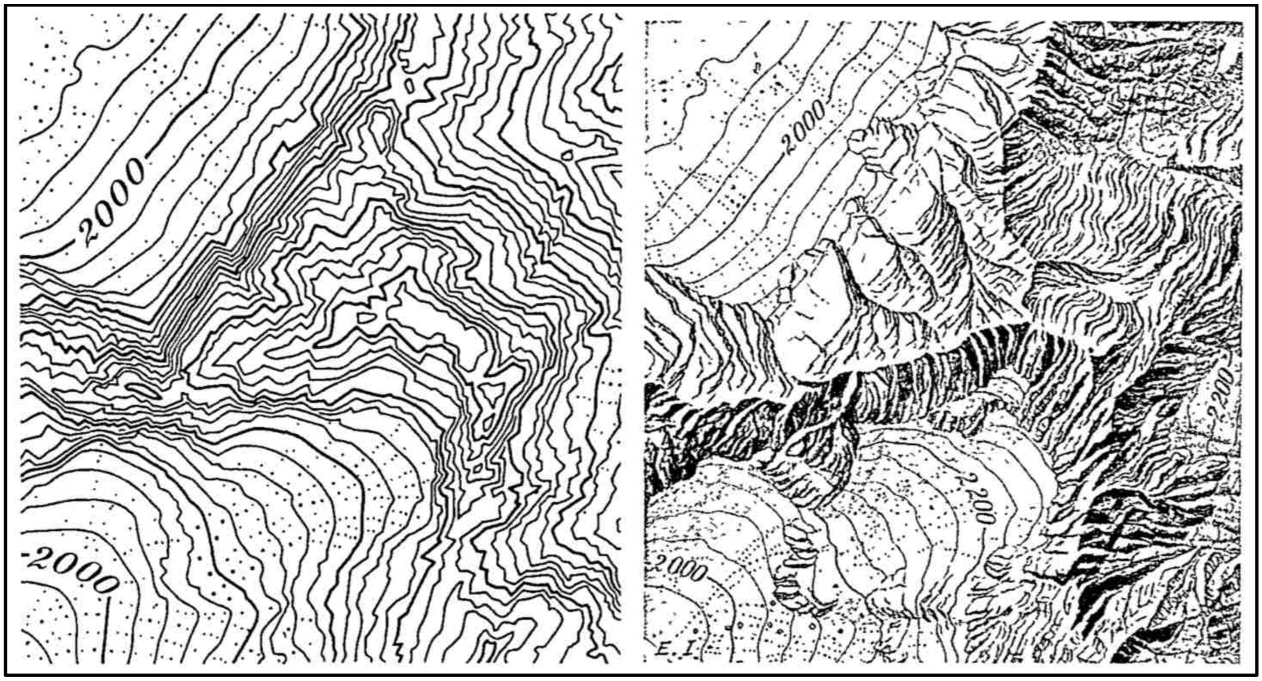


Figure 12. A comparison of conventional contours with contours, hillshade, and rock portrayal at the scale of 1:10,000. (Imhof, 2007, page 51)

In her 1992 textbook *Introduction to Thematic Cartography*, Tyner says that although contours and terrain are not thematic cartographic elements, they are reviewed in the textbook because of the ubiquity of terrain on maps. However, in her 2010 edition of *Principles of Map Design* there is not a chapter on terrain or contours and hardly a mention of terrain representation. I point this out because I wish to insert two critiques and ideas here: 1. Terrain *is* thematic (mapping that displays geographic data of specific areas in scientifically accurate and aesthetic ways) because of its scientific, artistic, and numerical value representational challenges and the multiple ways to visually represent it, and 2. I would argue that cognitive problems of terrain representations have not been wholly address or solved, but terrain representation and related topics have been pushed to the periphery of study due to the significant expansion, applications, and capability of computers and GIS that focus on non-terrain related spatial data, problems, and questions (Crampton and Krygier, 2006; McMaster & McMaster 2002).

Literature Review Part II

Theoretical Conceptions of Cognitive Map Design and Experimentation

The relationship between map user and cartographer has historically been a one way exchange. The cartographer has produced a map and said that the content signifies some spatial data, and it is up to the map user to understand it and consume the presented information at least somewhat accurately, or get lost in graphic confusion. A science must begin at some point, so the historical arbitrariness of cartography may not be so surprising and can be excused as necessary to begin building a science. Empirical research in cartographic cognition emerged in mid to late 20th century with cartographers drawing from psychology experiments that studied how people perceive graphic information. Cartographers began conducting their own psychological experiments focusing on maps as graphic and visual information (MacEachren, 1995). This emerging empirical research initiated a conversation between cartographer and audience to collect and analyze data that could be extrapolated into empirically supported map design principles. In *How Maps Work* (1995), MacEachren recounts experiments that considered the variability of untrained and trained map readers, and how human brains and eyes work to make sense of visual information in the form of patterns, features, proximity, scale, shape, colors, icons, and orientation.. Understanding human cognition in biophysical terms is a useful point of departure for thinking of how to present visual information because it can inform the designer of both what humans are physically capable of observing and how it is mentally understood.

Communication models between cartographer and map-reader is the focus of Robinson's book *The Look of Maps* (1952). As reviewed here, major and mainstream cartography textbooks by Raisz, Robinson, Imhof, and Tyner were conventionally the arbitrary cartographer speaking to aspiring cartographers to reify arbitrary cartographers' prescriptions to audiences without feedback or assessment of user cognition. The shift in cartography to have a two way conversation can be said to have formally begun with Robinson's *The Look of*

Maps, followed by applicable and extrapolatable psychological tests and cartographic cognition experiments (MacEachren, 1995), and has come to a prosperous point with cognitive experimentation and cartography textbooks acutely aware of audience on the receiving end of spatial information and maps, namely Cynthia Brewer's *Designing Better Maps*: A Guide for GIS Users (Brewer, 2005). Brewer (2005) focuses on map user understanding, and prescribes to cartographers best practices for color selection and use on maps. Her work is supported by extensive empirical work on how color on maps is understood, and how color selection can communicate most effectively various aspects of qualitative and quantitative data. Brewer (2005) initiates the reader and aspiring cartographer to consciously and consistently think of the map user, and suggests asking for critique on map design choices in order to take into account multiple perspectives and input. The constant attention to audience and presentation throughout the book is a progressive step forward for cartographic education.

In *The Look of Maps* (1952) Arthur Robinson calls for maps to be understandable to general map viewers by employing intuitive visual and cartographic techniques (McMaster & McMaster, 2002: Montello, 2002; Robinson, 1952). This was part of a shift in cartography from producing specialized maps mainly for military, elite, or academic use, to serving as tools of communication of spatial data to general audiences via thematic mapping (Dent, 1999, Imhof 2007; Robinson, 1952). Imhof (2007) addresses the same issue of cartographic design as in need of being understandable to general viewers in a very brief section of *Cartographic Relief Presentation* explicitly titled "Reform in Map Design." He states, "*Map design must be reformed*," and "The map should contain nothing that an average user cannot easily see." (Imhof, 2007, p. 359) He was aware of cognitive map testing being done in the USA, but thought that, "good training and gifted cartographers" (Imhof, 2007, p. 360) were more important than testing map user ability and comprehension.

Robinson identified a gap in the twentieth century cartographic literature, and an area of cognitive map design to approach and develop when he said, “Unfortunately nowhere in the literature of cartography is there any but passing treatment of the principles of visual design, except perhaps in connection with color” (p. 57). His discussion of cartographic techniques focused on text, line thickness, color, and projections, but the ideas of design principles he presents are applicable to cognitive map design of various phenomena, including terrain. Robinson put the arbitrariness of professional and academic cartography into question and critical critique by exploring how thematic mapping could be creative, standardized, and user friendly (Robinson, 1952). He posited two options for cartography: 1. “standardize everything” via cartographers’ arbitrary decision making to consistently use the same symbols and representations (“cities always would appear as black circles and they would be named in Spartan Medium Italic type, and so on” (Robinson, 1952, p. 19) so that all or most map users would eventually and assumedly become familiar with and accustomed to default map designs conventions, or 2. “study and analyze the characteristics of perception as they apply to the visual presentation we call a map” (Robinson, 1952, p. 19). He describes option one as absurd. Option two is a formation of cognitive map design study and practice. These two options are not mutually exclusive, as a synthesis of them can occur by developing standardized cartographic representations based on analyzed viewer perception, preference, and spatial comprehension. This synthesis is present in empirical research in map design dating to the 1970’s that had objectives of finding optimal representations based on categorization and classification that map viewers utilized accurately (MacEachren, 1995). MacEachren envisions how optimization efforts can function and be fruitful, saying:

> Improvements in information design (for maps and/or other graphics) could be expected to result through user training in the schemata employed by information designers and by information designers developing design schemata that match the general schemata of potential

> viewers in intuitive ways so they find it easy to adapt their general schemata to the particular case at hand. (MacEachren, 1995, page 210)

MacEachren brings together Robinson’s two options for cartography in reasonable, empirical, and applicable ways as conversation about critiquable visual content exchanged between cartographer (designer) and audience use and preference (schemata).

Robinson’s critique and proposals were followed by cartographers who began to consciously design maps with general map users in mind (Mark et al., 1999; Montello, 2002). Mark et al. explain cognitive map design well, stating that:

> Maps must provide accurate information to be useful, but they also must have an understandable message and be aesthetically pleasing. When cartographers began to study the nature of maps to understand symbolization and design principles (Robinson 1952, Robinson and Petchenik 1976), this resulted in an appreciation of maps as communication tools (Board 1967, KolaAny 1969) and the discovery of a need to understand the cognitive processes used by map readers. (Mark et al. 1999, page 754).

Having map users in mind during the cartographic production process acknowledges cognitive map design efforts but doesn’t fully address the issue because arbitrary cartography is still present because the map design is not based on users’ spatial task tests and research about how users actually view and understand maps, but instead on cartographic convention. Montello and Freunchschuh address this arbitrariness when discussing referents, iconicity, and conventionality:

> Symbolic representation occurs when a pattern of feature on a representation “stands for” something else… symbols vary in their arbitrariness/iconicity. This is essentially a question of the degree to which symbols resemble what they represent, their “referent”. Relatively iconic symbols have shape or other properties that are similar to those of the referent. Arbitrary symbols stand for their referent according to convention

> only. Contour lines on the topographic map represent elevation in a largely arbitrary way. (Montello & Freundschuh, 1995, page 174).

Contour lines are arbitrary, but hillshade may be an effective counterbalance to the arbitrariness of contours because hillshade is arguably a natural referent. Empirical research on how map-users understand maps has gathered map user data, assessed user experience, and analyzed spatial task performance, as well as visualization preferences (MacEachren, 1995; McMaster & McMaster, 2002; Monmonier, 1980; Montello, 2002; Montello, 2009; Nelson, 1996). This period arguably began after, and because of, Robinson's (1952) *The Look of Maps* (Montello, 2002; Robinson, 1952).

Assessing maps as communication tools stemmed from thematic mapping to investigate whether cartographic conventions are indeed communicative, informative, understandable, and intuitive to map viewers. This empirical work has studied map viewers' perceptions and spatial abilities with maps, and also includes historical cartographic conventionalities made by professional and academic cartographers who used their expertise and authority to establish what they thought or assumed was an effective cognitive representation that viewers would intuitively understand (Montello, 2002; Montello & Freundschuh, 1995; Patterson & Jenny, 2011). In some cases cartographers employ the use of representational tools and methods with their authority and experience in an to attempt to establish a cartographic conventionality (Bola & Samuel, 2014; Dent, 1999; Huffman & Patterson, 2013; Leonowicz et al., 2010; Patterson & Jenny 2011; Tyner 2010; Veronesi & Hurni, 2014). These design principles may seem reasonable or intuitive, but have not necessarily received robust support from empirical studies on map-user understanding. However, some studies have attempted to assess map-reader's understanding, employing Likert scales that analyze preference and opinions, tracking eye movement test to assess focus of attention, and tests that assess spatial task performance with maps (Alvarez et al., 2015; Biland & Çöltekin, 2017; Eynard & Jenny, 2016; Fabrikant et al., 2012; Kinnear & Wood, 1987; Lee & Bednarz, 2009; MacEachren, 1995; Patterson &

Jenny, 2013; Phillips et al., 1975; Pickle, 2003; Pingel & Clarke, 2014; Wheate, 1996).

Research indicates that map-readers generally understand contours on maps (Alvarez et al. 2015; Eynard & Jenny, 2016; Phillips et al., 1975). Research by Leonowicz et al. (2010) and Patterson (2015) argue that shaded relief is effective only at small or medium scales, in contrast to Robinson (1969) who argued that shaded relief is effective at all scales. Their expert advice is suitable to cartography only to the extent as professional conventionalities. It is not wholly supported by cognitive tests based on participant use and feedback. Another issue with hillshade technique is the often erroneous display of mountain tops and valley bottoms which sometimes are displayed as nonexistent (flat) or over exaggerated depending on the direction and angle of the illuminating light source (Biland & Çöltekin, 2017; Imhof, 2007; Raisz, 1948). There is not a gap in the literature on *how* to produce terrain representations, but there is a gap on *what* terrain representations are effective and at *what* scales.

Past studies on peoples' perception of terrain representations serve as the basis for the theoretical and methodological experimental foundations for this thesis. For example, Phillips et al. (1975) found that among layer tints, contours, hillshade, and "digital maps," the participants in their experiment located relative heights most accurately with layer tints (digital maps second, with contours and hillshade tied for third), and absolute heights most accurately with digital maps (contours and hillshade tied for second, layer tints last). Wheate (1996) found that people preferred hillshade representations over digital elevation model representations. Patterson and Jenny (2013) found that Americans associate the color green on maps with mountains, while Swiss and Germans associate the color brown with mountains. Biland and Çöltekin (2017) found that the optimal direction of the light source to create a hillshading effect on maps is 337.5 degrees (assuming 0 degree is north) as opposed to the conventional light source direction of 315 degrees. Finally, Eynard and Jenny (2016) found that map viewers more accurately identify elevation highs and lows with Tanaka contours (illuminated contours) than with conventional contours, shadowed contours, and hillshade. The topics and methods of these studies are influential to my approach to the thesis research, especially studies by Eynard and Jenny (2016) and Biland and Çöltekin (2017). This is mainly because they are experiments with map users pertaining to terrain cognition that employed the use of digital media (primarily computers) to collect map user responses and data. Biland's and Çöltekin's (2017) findings empirically inform the optimal direction of illumination for hillshade in order to correctly identify landforms. Participants for their study used a computer in controlled lab environment. When I initially produced maps for this research, I attempted to employ the principle Biland and Çöltekin found by adjusting the light source direction of a hillshade layer derived from a DEM to 337.5 degrees. However, this was not eventually presented in the experimentation because existing USGS maps were used instead. Eynard's and Jenny's research collected data via an online survey, as did the research for this thesis. The results of each study can be extrapolated into cognitive cartographic design principles as informed by the accuracy of participants, arguably a conceivable synthesis of Robinson's two options for cartography and a formation of MacEachren's envisioned relationship between designer and viewer.

Survey Design, Map Production, and Participants

The objective of this research was to assess how accurately map users estimate distance on the ground over changing elevations using conventional USGS maps that display terrain with contours and hillshade at various scales. An online survey was developed to assess:

1. How accurately participants estimated distance over changing terrain
2. If the presence of hillshade significantly affected distance estimate accuracy
   And
3. If scale had a significant affect on distance estimates

Nine maps were used in the survey (see appendix). The maps were produced with ArcMap version 10.6. Three maps were the controls for the study which were maps with no terrain features but only a linear feature laid over an OpenStreetMap basemap with no elevation characteristics. They acted as controls for the study by assessing if distance estimates that do not reference terrain vary significantly from estimates that do reference contours or contours and hillshade. The three maps with no elevation characteristics were at the scales of 1:24,000, 1:50,000, and 1:100,000. Two more sets of three maps consisted of contours and contours with hillshade. The three contour maps were also at the scales 1:24,000, 1:50,000, and 1:100,000, as were the three maps composed of contours with hillshade. The established USGS convention of contours with hillshade is present throughout the USGSTopo basemap used in ArcMap, so it was used for the maps with hillshade. The maps that had only contours at the scales of 1:24,000, 1:50,000, and 1:100,000 were obtained from the USGS topoview website as a GeoTIFF that was then opened in ArcMap. On each map a scale bar and representative fraction was displayed for participants to reference in estimating distance. The scale bar used is the same as is typically on USGS quadrangle maps. The maps with terrain characteristics additionally had contour intervals displayed.

The scales of 1:24,000, 1:50,000, and 1:100,000 were chosen for this study because they have historically been used by USGS and are still commonly employed by USGS and maps in general. The scales were also thought by the author to be different enough in size and scale to possibly elucidate differences in distance estimate accuracy because of scale. The terrain maps utilize portions of USGS topographic maps and imitate USGS design by using the same scale bar typically seen on USGS maps. No north arrows, compass roses, or legends were present. Minimal maps were an attempt to direct participant focus on the linear features and terrain without unnecessary distractions such as place or feature names. Areas were chosen based on terrain features, slope, and lack of place names participants may have recognized or been familiar with, i.e. mountain ranges, peaks, rivers, towns, etc. This was an effort to eliminate possibilities of participants' conscious familiarity or recognition of areas so that participants would attempt spatial tasks by using only terrain representations and other map elements. Areas of focus had slopes with significant changes in elevation.

Different geographic areas were displayed at different scales with no area being displayed more than once to negate a possible learning effect. Each map had a straight line labeled A at one end, and B at the other. Participants were asked to estimate the distance from A to B along that line. The map design template used for this study utilized the USGS's methodology of representing terrain via contours and hillshade.

The distance of the linear features on the maps used in the survey were initially measured in Google Earth as a KML file exported from ArcMap after being converted from a shapefile. An elevation profile of a linear feature is easy to produce in Google Earth and provides a two-dimensional distance and elevation increase and decrease, but not an overall three-dimensional distance of the feature as it changes in elevation over the ground. A similar problem came up when producing an elevation profile in ArcMap using a DEM as the basis for measurement. Instead of measuring the distance in Google Earth or with a DEM, distances were measured manually with the maps printed to scale. Two dimensional distances were measured by simply using a ruler. Three dimensional distances were measured by applying the Pythagorean theorem of $A^2 + B^2 = C^2$ to portions of the topographic maps. The Pythagorean theorem was applied to each slope on a map by measuring the two-dimensional distance with a ruler, providing the value for A, and calculating the elevation change with contour lines, providing the value for B. A and B were then squared which provided the value for C^2, then the square root of C^2 was calculated, providing an accurate approximation of the three-dimensional distance. Two-dimensional distances were calculated and recorded for the maps with no terrain. For the topographic maps, both two-dimensional and three-dimensional distances were calculated and recorded.

The online survey took approximately 5-10 minutes to complete. Google Forms was the survey tool of choice because it is free, it is mobile friendly, it can display images, it allows for multiple ways of answering questions (drop down menu, checkboxes, Likert scales, text input, etc.), and the data can be downloaded in tabular format and opened in Excel.

The research protocol used in this study was approved by the University of New Mexico's Institutional Review Board. Participation was voluntary and confidential. No personally identifying information was requested or recorded. Participants were not compensated for their participation. The only requirements for participation were to be at least 18 years of age or older and have internet access. Participant data included consent to participate, demographics, and linear distance estimations. Demographic questions included:

- What is your age in years?
- What is your country of origin?
- What is your gender?
- What is the highest level of education you have completed? If currently enrolled please select the current level.
- How experienced are you with topographic maps?
- What type of device are you currently using to participate in this research?

Participants typed their answers for the questions on age, country of origin, and gender. A drop-down selection was used for answering level of education and type of device used, and a Likert scale was used to answer the question on experience with topographic maps. Participants typed their answers to the map reading questions as numerical values.

The survey was online and open for participation from 2/12/19 to 3/18/19. Recruitment of participants was done via word of mouth, online discussion boards, flyers posted on UNM's main campus, and online social media. A total of 144 responses were collected. Two individuals did not agree to participate in the research, and three responses were deleted from the dataset altogether due to being incomplete or nefariously incorrect. This brought the total number of participants used in data analyses to 139.

Demographics

Participant ages ranged from 19 to 72. Sixty participants were in the subgroup age range of 19-29, 42 in the subgroup age range of 30-39, 25 in the subgroup age range of 40-49, 8 in the subgroup age range of 50-59, and 4 in the subgroup age range of 60-72 (Table 1). For the country of origin demographic data one person was from Australia, one from Austria, 18 from Canada, one from Chile, one from France, five from Germany, one from Ghana, one from Israel, two from Kenya, two from The Netherlands, one from North Korea, one from Spain, one from Switzerland, eight from The UK, and 95 from The USA (Table 2). Thirty-one participants were female, 105 male, and two non-binary (Table 3). For the highest level of education attained, two participants had associate’s degrees, 69 had bachelor’s degrees, 6 had doctorate degrees, one had an elementary education, two a high school diploma or GED, 36 a master’s degree, one a professional degree, 20 had some college, and two had trade/technical/vocational training (Table 4). The question of experience with topographic maps was answered via a Likert scale with 1 being not experienced at all and 5 being very experienced. Four participants said they had tier 1 experience with topographic maps, 17 tier 2, 38 tier 3, 38 tier 4, and 42 tier 5 (Table 5). Seventy-nine participants used a laptop/desktop computer to access the survey, 55 a phone, and 5 a tablet (Table 6).

Age Groups	Number of Participants
19-29	60
30-39	42
40-49	25
50-59	8
60-72	4

Table 1. Age group demographics

Country of Origin	Number of Participants
Australia	1
Austria	1
Canada	18
Chile	1
France	1
Germany	5
Ghana	1
Israel	1
Kenya	2
Netherlands	2
North Korea	1
Spain	1
Switzerland	1
UK	8
USA	95

Table 2. Country of origin demographics

Gender	Number of Participants
Female	31
Male	105
Non-Binary	2

Table 3. Gender demographics

Education	**Number of Participants**
Elementary	1
High School/GED	2
Some College	20
TradeVoTech	2
Associate’s	2
Bachelor’s	69
Master’s	36
Professional	1
Doctorate	6

Table 4. Education demographics

Experience with Topo Maps	**Number of Participants**
1 (Not experienced at all)	4
2	17
3	38
4	38
5 (Very Experienced)	42

Table 5. Experience demographics

Device	**Number of Participants**
Laptop/Desktop	79
Phone	55
Tablet	5

Table 6. Device demographics

Results

Participant data was downloaded from Google Forms as a csv file readable and editable in Microsoft Excel. The data was organized and cleaned, i.e., all gender answers of “female” were normalized to “Female” with a capital F and no spaces, country of origin answers of “Us,” “United States,” or “United States of America” were normalized to “USA,” etc. All data analysis was done within Excel. The software package add on Analyse-It was used within Microsoft Excel to run ANOVA tests , the add-in Analysis Toolpak in Microsoft Excel was used to run t-tests, and descriptive statistics were calculated in Microsoft Excel.

Percent accuracy was calculated using the formula: Observed Value – Actual Value / Actual value x 100. The value the formula yielded was the percent error which was then subtracted from 100 to provide the percent accuracy. Percent accuracy was calculated for each individual estimate then averaged for demographic groups. Overall, participants estimated most accurately with the map at a scale of 1:100,00 with no terrain with an average 87% accuracy, and least accurately with the map at the scale of 1:50,000 composed of contours with an accuracy of 74% compared against the two-dimensional distance (Table 7). Overall participant accuracy for all maps was 81%. Per map type, participants average accuracy was 84% with no terrain, 80% with contours, and 80.5% with contours and hillshade (Table 8). Per scale, participants average accuracy was 81% for maps at the scale of 1:24,000, 79% for maps at the scale of 1:50,000, and 82% for maps at the scale of 1:100,000 (Table 9). For age groups, participants 19-29 had an average of 80% accuracy, 30-39 80% accuracy, 40-49 82% accuracy, 50-59 89% percent accuracy, and 60-72 85% accuracy (Table 10). Among country of origin data, Chile had the highest average accuracy at 94% and Ghana had the lowest at 8% (Table 11). Accuracy results of Americans in particular were of interest to see if Americans perform better with USGS maps than other nationalities, as USGS maps are products of the American government. In terms of average accuracy by country of origin, Americans are tied for sixth place with Austrians, being outperformed by participants from France, Germany, North Korea, and Switzerland. Among gender data the average accuracy was 83% for females, 80% for males, and 76% for non-binary (Table 12). Among educational backgrounds, participants with elementary and trade/vocational/technical as their highest education attainment had the highest average accuracy at 92%, and participants with an associate's degree had the lowest average accuracy at 69% (Table 13). Among experience with topographic maps, group 1 had an average accuracy of 49%, group 2 77%, group 3 83%, group 4 86%, and group 5 80% (Table 14). Among devices used to participate, those who used a laptop/desktop had the highest average accuracy at 82%, with tablet users at 80%, and phone users at 78% (Table 15).

Map	Average Accuracy
1:24,000 No Terrain	85%
1:24,000 Contours 3D	82%
1:24,000 Contours 2D	81%
1:24,000 Contours and Hillshade 3D	80%
1:24,000 Contours and Hillshade 2D	79%
1:50,000 No Terrain	81%
1:50,000 Contours 3D	75%
1:50,000 Contours 2D	74%
1:50,000 Contours and Hillshade 3D	84%
1:50,000 Contours and Hillshade 2D	83%
1:100,000 No Terrain	87%
1:100,000 Contours 3D	84%
1:100,000 Contours 2D	84%
1:100,000 Contours and Hillshade 3D	79%
1:100,000 Contours and Hillshade 2D	78%

Table 7. Average accuracy per map

Map Type	Average Accuracy
No Terrain	84%
Contours	80%
Contours and Hillshade	80.5%

Table 8. Average accuracy per map type

Map Scale	Average Accuracy
1:24,000	81%
1:50,000	79%
1:100,000	82%

Table 9. Average accuracy per scale

Age Groups	Average Accuracy
19-29	80%
30-39	80%
40-49	82%
50-59	89%
60-72	85%

Table 10. Average accuracy per age group

Country of Origin	Average Accuracy
Australia	65%
Austria	84%
Canada	78%
Chile	94%
France	88%
Germany	88%
Ghana	8%
Israel	78%
Kenya	47%
Netherlands	77%
North Korea	92%
Spain	78%
Switzerland	88%
UK	74%
USA	84%

Table 11. Average accuracy per country of origin

Gender	Average Accuracy
Female	83%
Male	80%
Non-Binary	76%

Table 12. Average accuracy per gender

Education	Average Accuracy
Elementary	92%
High School/GED	84%
Some College	86%
TradeVoTech	92%
Associate’s	69%
Bachelor’s	81%
Master’s	77%
Professional	87%
Doctorate	81%

Table 13. Average accuracy per education

Experience with Topo Maps	Average Accuracy
1 (Not experienced at all)	49%
2	77%
3	83%
4	86%
5 (Very Experienced)	80%

Table 14. Average accuracy per experience

Device	Average Accuracy
Laptop/Desktop	82%
Phone	78%
Tablet	80%

Table 15. Average accuracy per device

The two and three-dimensional distance measurements were analyzed and compared with participant estimates and participant estimate deviations. To find the deviation of each response, participant estimates were subtracted from the two-dimensional and three-dimensional values. Both two and three-dimensional values for topographic maps were assessed because it was unsure if participants were estimating distance as a straight line (as the crow flies) or actual ground distance considering elevation change.

The deviations of individual responses from the average for each demographic group were compared against the two-dimensional and three-dimensional distances via ANOVA tests. In comparing against two-dimensional distances for the maps with no terrain and both two-dimensional and three-dimensional distances with the topographic maps, each demographic group underwent 15 ANOVA tests. In total 90 ANOVA tests were conducted to analyze participant estimates based on age, country of origin, gender, education, experience, and device. No significant results were found among age, gender, or experience with topographic maps (Tables 16, 17, and 18). Seven ANOVA tests yielded a significant p-value in the categories of country of origin, device, and education. These significant results are highlighted in grey in Tables 19, 20, and 21. Significance was found when analyzing participant estimates grouped by country for the two and three-dimensional distances of the map at a scale of 1:24,000 composed of contours and hillshade. This result is likely due to one estimate by a Dutch participant whose estimate for that map deviated by 40,588 from the three dimensional distance and 41,000 from the two-dimensional distance. Significance was found when analyzing participant estimates grouped by device used to participate for the two and three-dimensional distances of the map at a scale of 1:50,000 composed of contours. This result is likely due to one estimate from a participant who used a tablet whose estimate for that map deviated by 41,154 from the three-dimensional distance and 41,250 from the two-dimensional distance. Significance was found when analyzing participant estimates grouped by education for the two-dimensional distance of the map with no terrain at the scale of 1:24,000 and the two and three-dimensional distances of the map at the scale of 1:100,000 composed of contours. It is unclear why this resulted for these maps when analyzing by educational groups. The small number of significant results from ANOVA tests only being in present in seven out of 90 tests suggests that there is not a substantial difference among the demographic groups ability at estimate distance, either two-dimensional or three-dimensional. This suggestion can also be seen in the overall average accuracy results as percentages (Table 7).

Stimuli	**F, P-Value**
1:24,000 No Terrain	0.97, 0.5227
1:24,000 Contours 3D	1.24, 0.1982
1:24,000 Contours 2D	1.24, 0.1982
1:24,000 Contours and Hillshade 3D	0.51, 0.9904
1:24,000 Contours and Hillshade 2D	0.51, 0.9904
1:50,000 No Terrain	0.86, 0.6967
1:50,000 Contours 3D	0.77, 0.8190
1:50,000 Contours 2D	0.77, 0.8190
1:50,000 Contours and Hillshade 3D	0.50, 0.9911
1:50,000 Contours and Hillshade 2D	0.50, 0.9911
1:100,000 No Terrain	0.66, 0.9291
1:100,000 Contours 3D	0.48, 0.9941
1:100,000 Contours 2D	0.48, 0.9941
1:100,000 Contours and Hillshade 3D	0.63, 0.9484
1:100,000 Contours and Hillshade 2D	0.63, 0.9484

Table 16. ANOVA results for age

Stimuli	**F, P-Value**
1:24,000 No Terrain	0.09, 0.9663
1:24,000 Contours 3D	0.66, 0.5790
1:24,000 Contours 2D	0.66, 0.5790
1:24,000 Contours and Hillshade 3D	0.38, 0.7659
1:24,000 Contours and Hillshade 2D	0.38, 0.7660
1:50,000 No Terrain	0.31, 0.8194
1:50,000 Contours 3D	0.04, 0.9911
1:50,000 Contours 2D	0.04, 0.9911
1:50,000 Contours and Hillshade 3D	0.04, 0.9909
1:50,000 Contours and Hillshade 2D	0.04, 0.9910
1:100,000 No Terrain	0.12, 0.9473
1:100,000 Contours 3D	1.42, 0.2397
1:100,000 Contours 2D	1.42, 0.2397
1:100,000 Contours and Hillshade 3D	1.40, 0.2447
1:100,000 Contours and Hillshade 2D	1.40, 0.2447

Table 17. ANOVA results for gender

Stimuli	F, P-Value
1:24,000 No Terrain	0.99, 0.4167
1:24,000 Contours 3D	0.51, 0.7313
1:24,000 Contours 2D	0.51, 0.7313
1:24,000 Contours and Hillshade 3D	0.82, 0.5168
1:24,000 Contours and Hillshade 2D	0.82, 0.5168
1:50,000 No Terrain	1.04, 0.3890
1:50,000 Contours 3D	0.44, 0.7815
1:50,000 Contours 2D	0.44, 0.7815
1:50,000 Contours and Hillshade 3D	0.57, 0.6878
1:50,000 Contours and Hillshade 2D	0.57, 0.6878
1:100,000 No Terrain	1.58, 0.1842
1:100,000 Contours 3D	0.70, 0.5912
1:100,000 Contours 2D	0.70, 0.5912
1:100,000 Contours and Hillshade 3D	0.60, 0.6609
1:100,000 Contours and Hillshade 2D	0.60, 0.6609

Table 18. ANOVA results for experience with topographic maps

Stimuli	F, P-Value
1:24,000 No Terrain	0.19, 0.9994
1:24,000 Contours 3D	0.90, 0.5593
1:24,000 Contours 2D	0.90, 0.5593
1:24,000 Contours and Hillshade 3D	3.87, <0.0001
1:24,000 Contours and Hillshade 2D	3.87, <0.0001
1:50,000 No Terrain	0.36, 0.9829
1:50,000 Contours 3D	0.10, 1.000
1:50,000 Contours 2D	0.10, 1.000
1:50,000 Contours and Hillshade 3D	0.06, 1.000
1:50,000 Contours and Hillshade 2D	0.06, 1.000
1:100,000 No Terrain	0.41, 0.9697
1:100,000 Contours 3D	0.19, 0.9994
1:100,000 Contours 2D	0.19, 0.9994
1:100,000 Contours and Hillshade 3D	0.51, 0.9218
1:100,000 Contours and Hillshade 2D	0.51, 0.9218

Table 19. ANOVA results for country of origin

Stimuli	**F, P-Value**
1:24,000 No Terrain	1.16, 0.3153
1:24,000 Contours 3D	0.38, 0.6831
1:24,000 Contours 2D	0.38, 0.6831
1:24,000 Contours and Hillshade 3D	0.13, 0.8818
1:24,000 Contours and Hillshade 2D	0.13, 0.8818
1:50,000 No Terrain	0.98, 0.3786
1:50,000 Contours 3D	16.80, <0.0001
1:50,000 Contours 2D	16.80, <0.0001
1:50,000 Contours and Hillshade 3D	0.44, 0.6435
1:50,000 Contours and Hillshade 2D	0.44, 0.6435
1:100,000 No Terrain	0.53, 0.5924
1:100,000 Contours 3D	0.79, 0.4559
1:100,000 Contours 2D	0.79, 0.4559
1:100,000 Contours and Hillshade 3D	0.32, 0.7291
1:100,000 Contours and Hillshade 2D	0.32, 0.7291

Table 20. ANOVA results for device

Stimuli	**F, P-Value**
1:24,000 No Terrain	2.48, 0.0155
1:24,000 Contours 3D	1.56, 0.1424
1:24,000 Contours 2D	1.56, 0.1424
1:24,000 Contours and Hillshade 3D	0.50, 0.8567
1:24,000 Contours and Hillshade 2D	0.50, 0.8567
1:50,000 No Terrain	0.17, 0.9945
1:50,000 Contours 3D	0.56, 0.8090
1:50,000 Contours 2D	0.56, 0.8090
1:50,000 Contours and Hillshade 3D	0.07, 0.9998
1:50,000 Contours and Hillshade 2D	0.07, 0.9998
1:100,000 No Terrain	0.46, 0.8810
1:100,000 Contours 3D	2.65, 0.0100
1:100,000 Contours 2D	2.65, 0.0100
1:100,000 Contours and Hillshade 3D	0.51, 0.8459
1:100,000 Contours and Hillshade 2D	0.51, 0.8459

Table 21. ANOVA results for education

Two-sample t-tests assuming equal variances were conducted with the Analysis ToolPak in Microsoft Excel to investigate any significant results among the means of participant estimates in terms of map type and scale. In these tests, one variable was the estimates, and the other variable was the correct two and three dimensional distances. A test was done with participant estimates for each map reading question along with two and three dimensional distances for maps with terrain. Maps with no terrain underwent only one t-test because only the two dimensional distance was analyzed. A total of fifteen t-test were completed. Three tests resulted in significant p-values which reject the null hypothesis. These significant results are highlighted in grey in tables 22 and 23. The map at the scale of 1:24,000 composed of contours yielded a significant p-value with the other variable being the correct two dimensional distance. The map at the scale of 1:50,000 composed of contours yielded a significant p-value with the other variable being the correct two dimensional distance, as well the correct three dimensional distance. These significant p-values are likely due to the large variance in estimates for these maps and this may suggest that participants were in general less accurate at estimating distance with contours only at large to mid scales.

1:24,000	**T, P-value**	**1:50,000**	**T, P-value**	**1:100,000**	**T, P-value**
No Terrain	0.50, 0.6119	No Terrain	-0.11, 0.9069	No Terrain	0.23, 0.8125
Contours 3D	-0.38, 0.6984	Contours 3D	2.52, 0.0122	Contours 3D	-1.39, 0.1629
Contours 2D	2.46, 0.0141	Contours 2D	2.79, 0.0055	Contours 2D	-0.02, 0.9800
Contours & Hillshade 3D	0.78, 0.4333	Contours & Hillshade 3D	0.67, 0.5030	Contours & Hillshade 3D	-0.67, 0.4994
Contours & Hillshade 2D	1.96, 0.0508	Contours & Hillshade 2D	1.27, 0.2022	Contours & Hillshade 2D	-1.3, 0.1944

Table 22. t-test results grouped by scale

No Terrain	**T, P-Value**	**Contours**	**T, P-Value**	**Contours & Hillshade**	**T, P-value**
1:24,000	0.50, 0.6119	1:24,000 3D	-0.38, 0.6984	1:24,000 3D	0.78, 0.4333
1:50,000	-0.11, 0.9069	1:24,000 2D	2.46, 0.0141	1:24,000 2D	1.96, 0.0508
1:100,00	0.23, 0.8125	1:50,000 3D	2.52, 0.0122	1:50,000 3D	0.67, 0.5030
		1:50,000 2D	2,79, 0.0055	1:50,000 2D	1.27, 0.2022
		1:100,000 3D	-1.39, 0.1629	1:100,000 3D	-0.67, 0.4994
		1:100,000 2D	-0.02, 0.9800	1:100,000 2D	-1.30, 0.1944

Table 23. t-test results grouped by map type

Discussion

No statistically significant results were found in terms of demographics, map type, or scale via ANOVA tests. The statistically significant results yield via ANOVA and t-tests is likely due to a large variance among estimates and can be interpreted as meaning participants were overall less accurate with the maps yielding statistically significant results. The significant t-test results are of interest because they suggest that maps at large to mid scales composed of contours and lacking hillshade are more difficult for people to estimate distance with. Further, this may suggest that maps at large to mid scales with contours and supplemented with hillshade may be more useful than contours alone for estimating distance because of the presence of hillshade.

In general, each demographic group estimated fairly well, with some outliers and small demographic groups present in the data. For example, in the country of origin data one participant was from Ghana and estimated inaccurately, and non-binary individuals are present in the data but also a small subgroup numbering two. The few significant statistical ANOVA tests do not contribute to any reasonable generalizations about demographics, map type, or scale because the significant results occurred for different demographics and different scales. The results show that the presence of terrain representations and variability of scale in general has no effect on estimates, except in the three cases of the significant t-test results Participants were generally consistent in their estimate accuracy regardless of map type or scale. While there were some estimates that extremely deviated from the correct distance, it can be concluded that map users in general can read topographic maps with contours fairly well. From this research it can empirically be stated that people read distance on topographic maps correct 81% of the time.

Limitations and Further Research

This study was limited by having only one type of each map at one scale. A more in-depth experiment could present multiple maps of the same kind and scale to obtain an average accuracy for each map type and scale. The map with contours only at the scale of 1:50,000 was dissimilar from the rest and the terrain was difficult to read causing unusual or outlier results among the dataset. It was difficult to find a USGS map with contours only at the scale of 1:50,000, so I worked with what I could find. The hillshade effect in the USGS maps used in the survey is unpronounced compared to other hillshades, such as that in Google Terrain. Further studies could employ a more dramatic and pronounced hillshade layer with custom maps, or use multi-directional hillshade (hillshade effect with up to six directions of illumination). This research had no funding and a survey that obtains more participants willing to answer more questions on map reading would likely be more successful with incentives for participating. Participation was limited by not allowing people under the age of 18 to participate. This was done for practical reasons to satisfy The Institutional Review Board limitations and requirements. Additional research could study how people under the age of 18 comprehend topographic maps. Further research on how accurately map users estimate distance could incorporate other terrain representations such as hypsometric tints, hypsometric tints with contours, slope DEMs, slope DEMS with contours, etc. Other scales would be interesting to study as well, such as large scale topographic maps at 1:10,000, or small scale at 1:250,000. The two and three-dimensional distances for the maps used in the survey may not be different enough to account for participants thinking two or three dimensionally or different enough to even matter to a statistically significant degree. The largest difference among two and three-dimensional distances among the maps is only 743 units, with the other maps having just a couple hundred units of difference. Maps that ask for a distance estimate that has a three-dimensional distance substantially different from the two dimensional distance may need to have a linear feature over a larger or steeper area, or ask for three dimensional distance as a path with changing orientations such as a trail or road with multiple switchbacks instead of a straight linear feature.

Conclusion

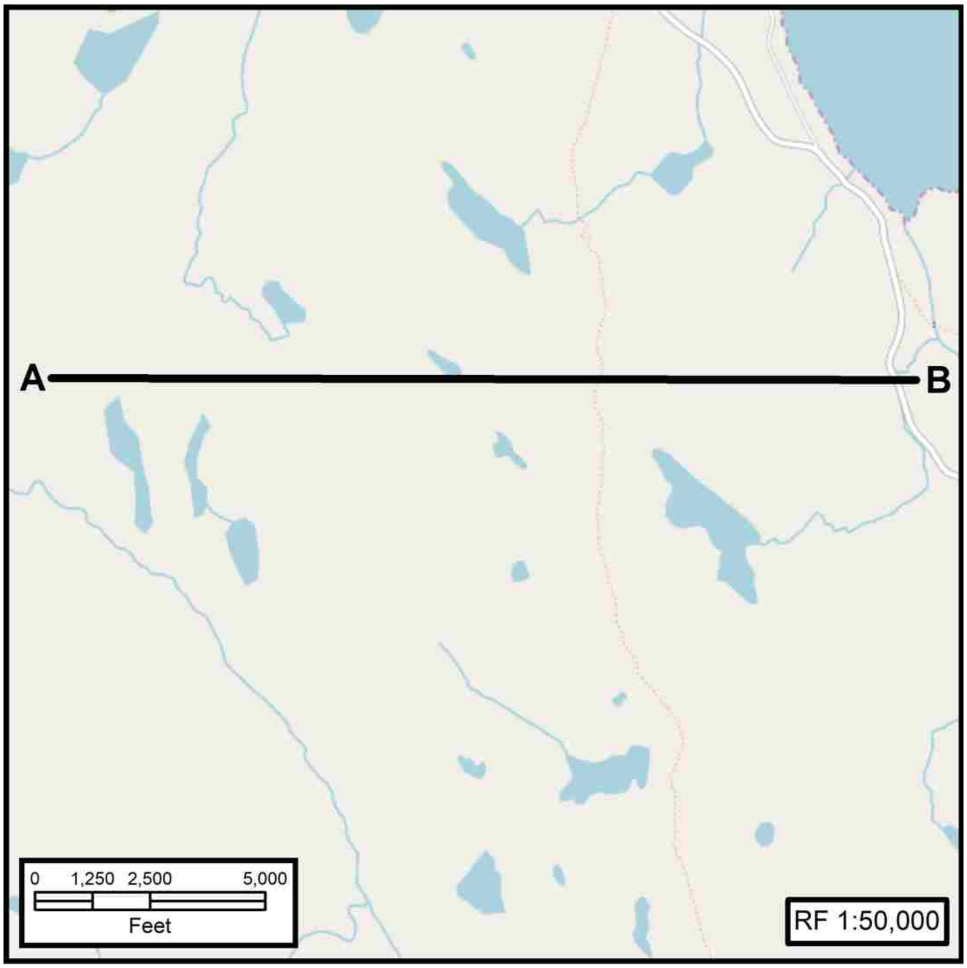
It seems that Raisz, Robinson, Tyner, and Imhof have been correct in praising the conventional combination of contours and hillshade to cartographically represent terrain. Though, the utility of contours and hillshade may be well established because of cartographers such as them, which then causes map users to have some requirement to know how to understand the presented spatial information. The academic geographic community and map users can somewhat confidently be aware of how accurately they do comprehend terrain with topographic maps.

Applications

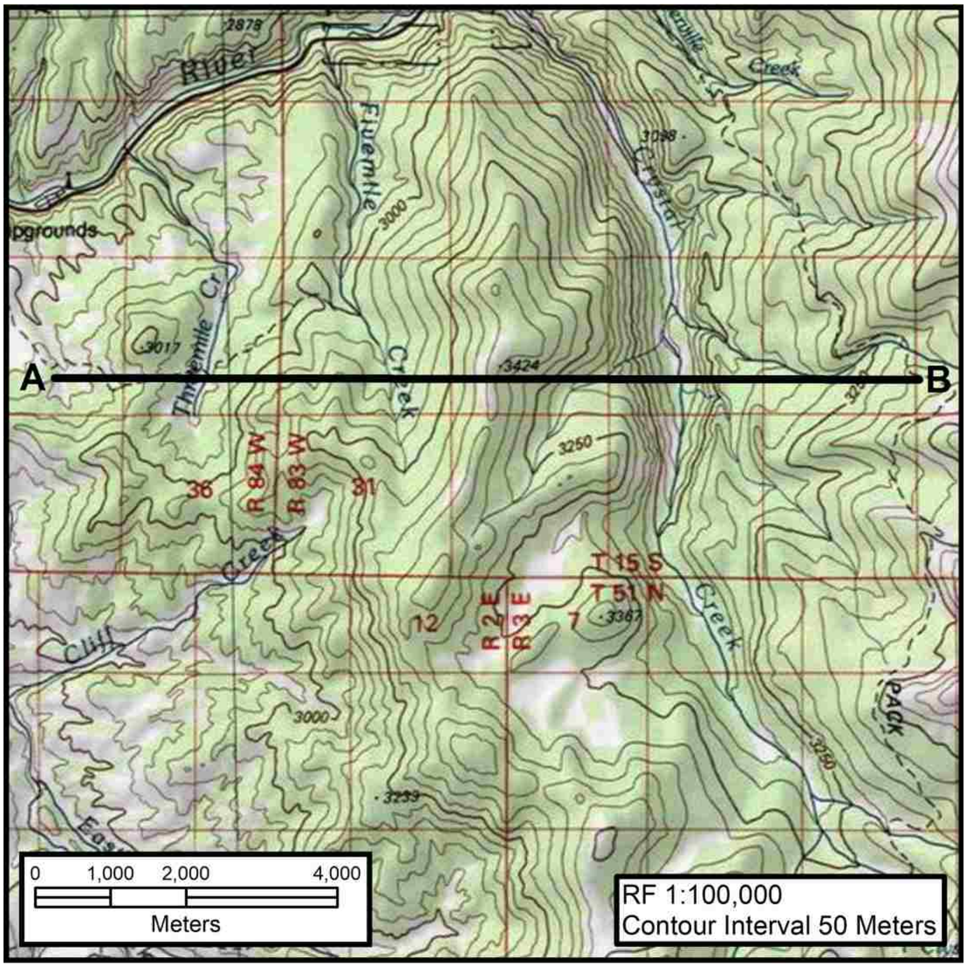
The results of this research can be applied to outdoor recreation activities (hiking, mountain biking), forest and park planning (for agencies such as the National Park Service, U.S. Forest Service, state parks), and disaster response (first responders, search and rescue, wildland firefighting) by knowing what terrain representations general audiences or specific groups (as specific as demographic data can be used towards) understand and can utilizing well. Places such as trailheads should have map, and instead of it being a map with no terrain or composed of satellite imagery it should have terrain on it, either as contours or contours with hillshade. Land management agencies should always publish visitor maps with terrain information present. With well designed topographic maps people can understand and accurately conceive elevation changes and distances over terrain in order to anticipate approximate travel times and difficulties due to elevation changes.

Appendix

This appendix contains the maps used in the survey. They are in the same order as they were when presented to participants and the correct distances are displayed below the image.

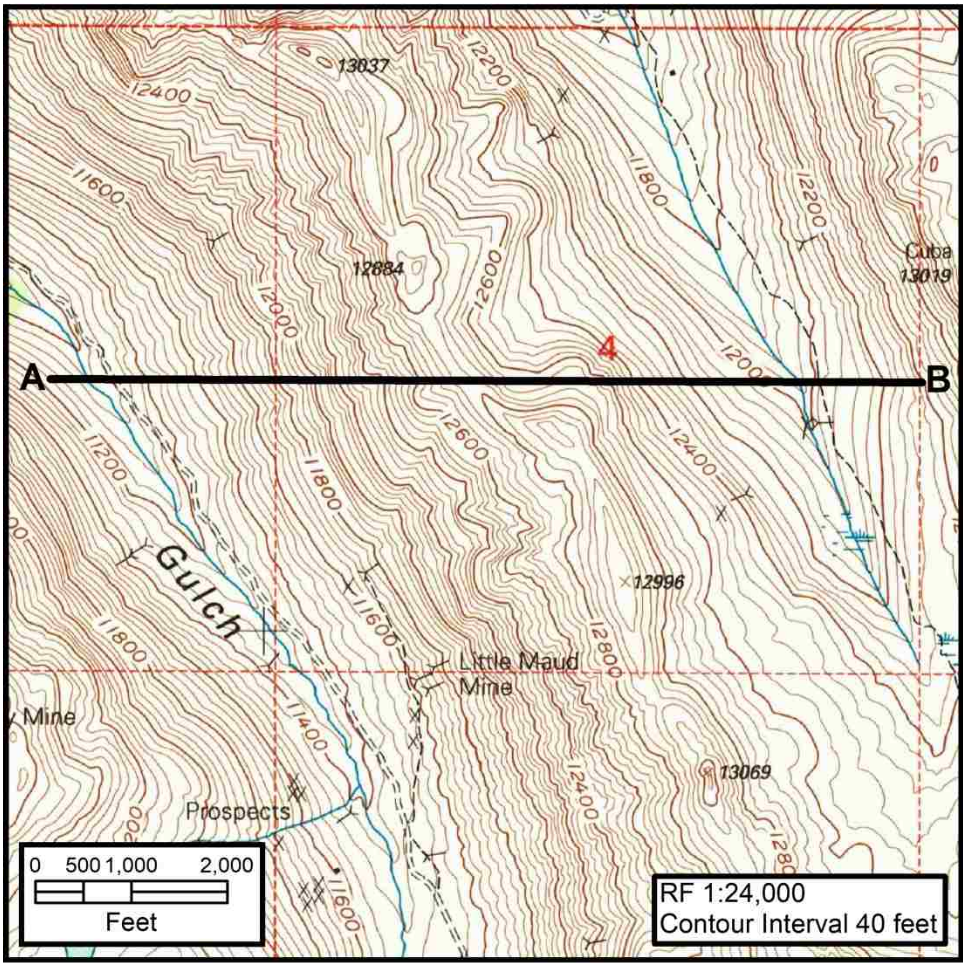


2D: 19,167 Feet



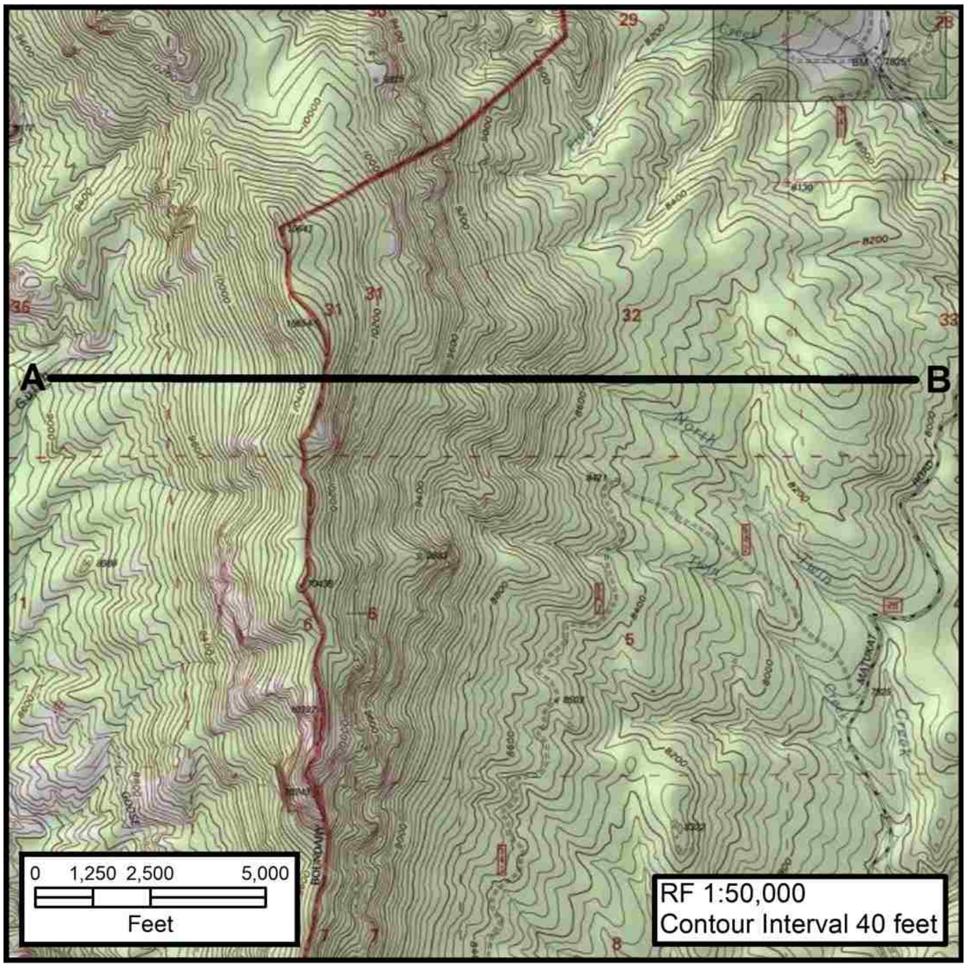
2D: 11,500 Meters

3D: 11,733 Meters



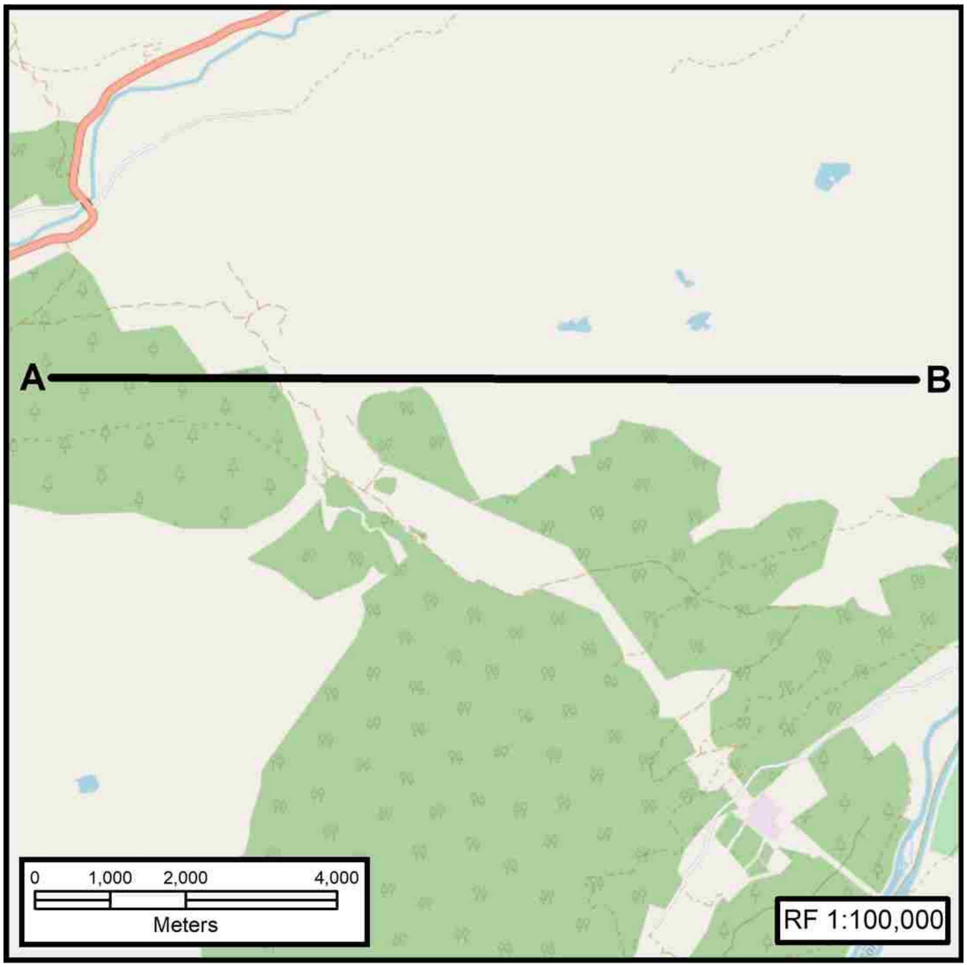
2D: 9,000 Feet

3D: 9,597 Feet

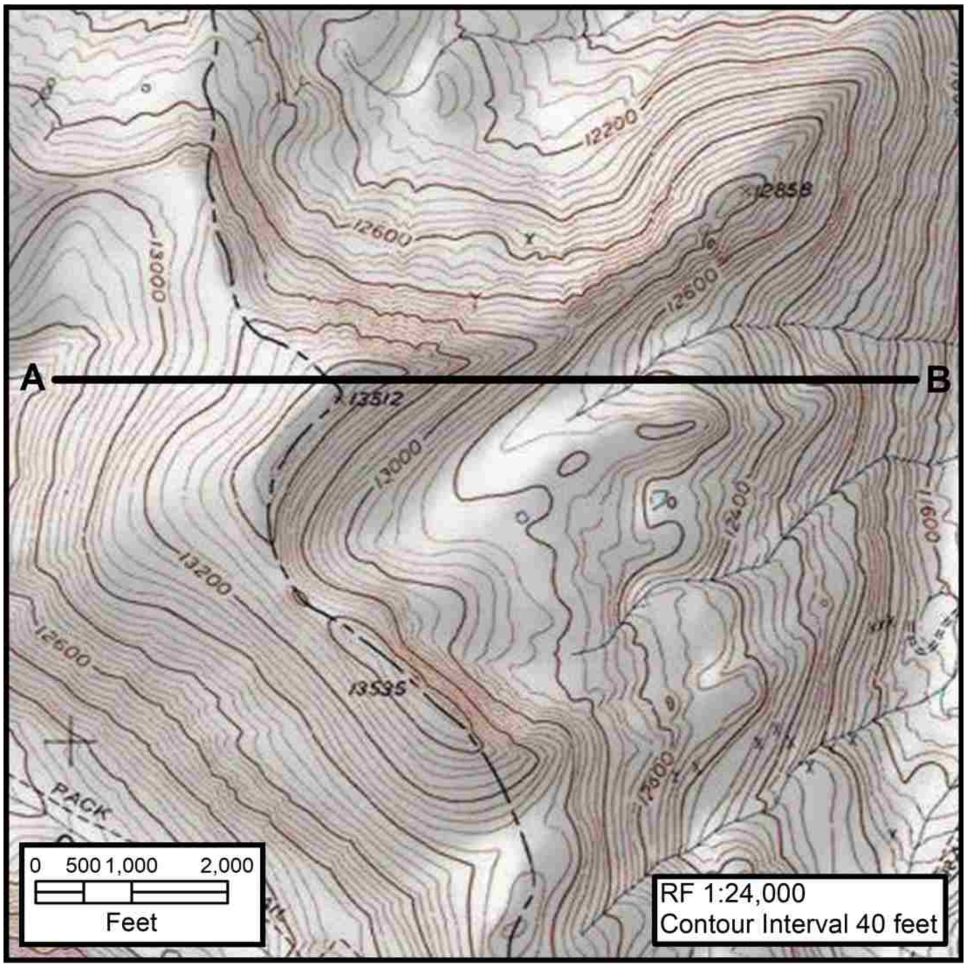


2D: 19,166 Feet

3D: 19,909 Feet

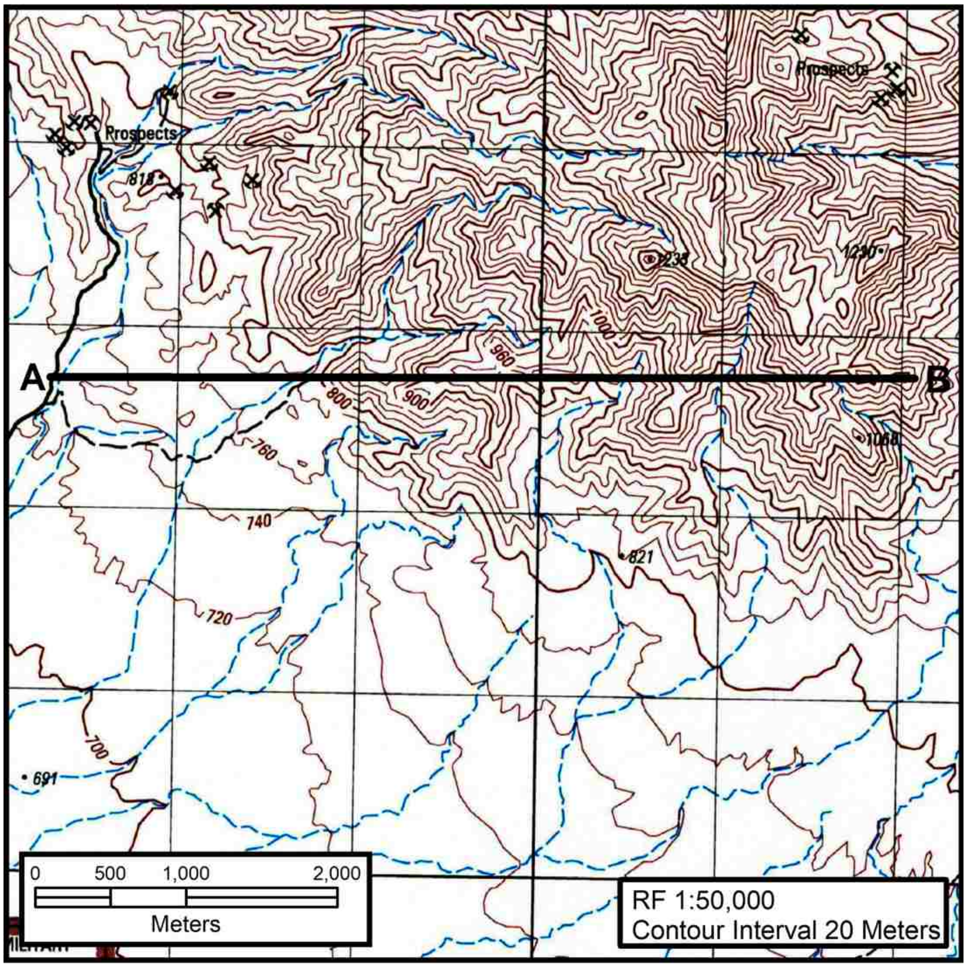


2D: 11,500 Meters



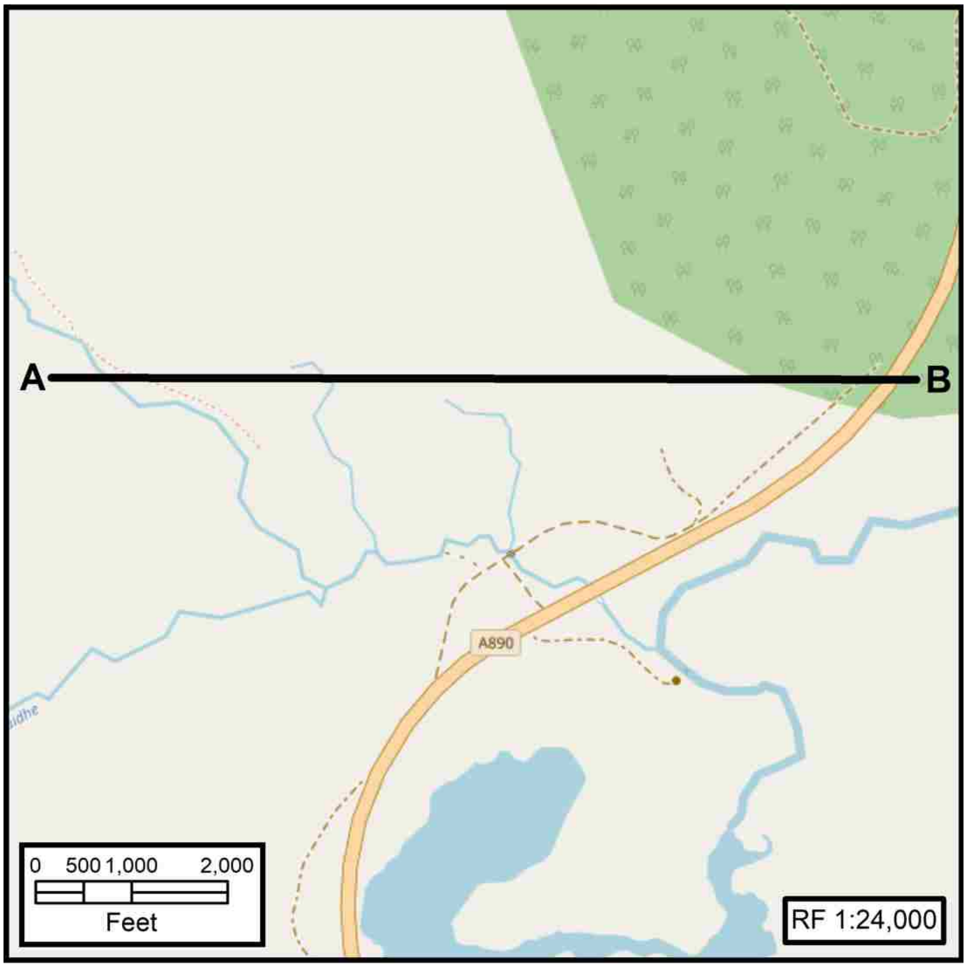
2D: 9,000 Feet

3D: 9,412 Feet

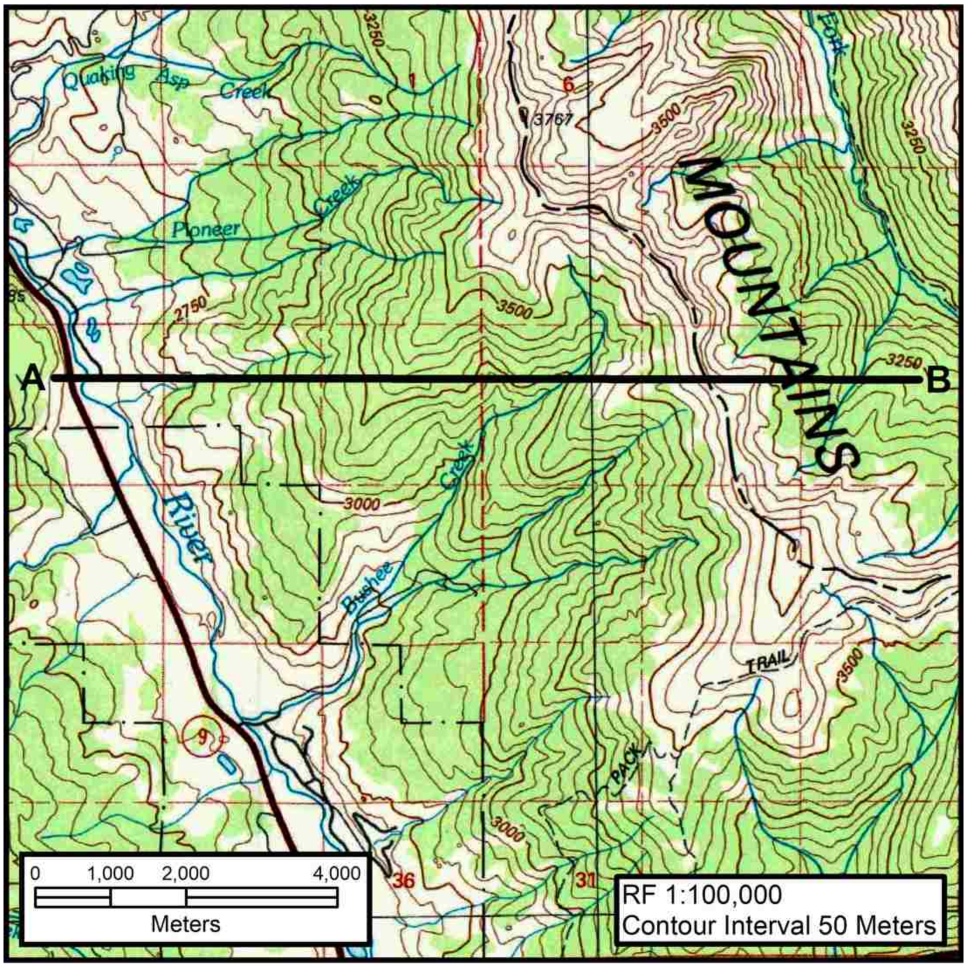


2D: 5,750 Meters

3D: 5,846 Meters



2D: 9,000 Feet



2D: 11,500 Meters

3D: 11,881 Meters

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