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International Journal of Geographical Information Science

ISSN: 1365-8816 (Print) 1362-3087 (Online) Journal homepage: http://www.tandfonline.com/loi/tgis20

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To cite this article: James D. Eynard & Bernhard Jenny (2016): Illuminated and shadowed contour lines: improving algorithms and evaluating effectiveness, International Journal of Geographical Information Science

To link to this article: http://dx.doi.org/10.1080/13658816.2016.1144885

Published online: 07 Apr 2016.

INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE, 2016
http://dx.doi.org/10.1080/13658816.2016.1144885

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Illuminated and shadowed contour lines: improving algorithms and evaluating effectiveness

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ABSTRACT

Shadowed contour lines vary line width. Illuminated contour lines additionally vary color based on an angle of illumination. Illuminated and shadowed contour lines date back to the mid-nineteenth century, but their effectiveness compared to conventional contour lines has not been fully examined. Currently, illuminated and shadowed contour lines are not widely used in computer-based cartography because they are not included in most GIS apmaking software. This article introduces improvements to existing algorithms for creating illuminated and shadowed contour lines from digital elevation data. A software package is made available to allow mapmakers to more easily make customized illuminated and shadowed contour maps. A user study comparing illuminated and shadowed contour lines to conventional contour lines and shaded relief with approximately 400 participants was conducted. Results indicate that map-readers can interpret relative height differences between points better and quicker with illuminated contour lines than regular contour lines or shaded relief. Study participants were able to select absolute maxima on an unlabeled illuminated contour map and a labeled regular contour map with equal accuracy and speed. These findings suggest that illuminated contour lines could be used more frequently for improved visualization of terrain and other surface data on maps.

ARTICLE HISTORY

Received 13 February 2015
Accepted 31 December 2015

KEYWORDS

Illuminated contour lines; shadowed contour lines; Tanaka contour lines

1. Introduction

Contour lines, also known as isolines, represent surfaces of continuous data as lines joining points of equal value. Contour lines often depict lines of constant elevation, but are also frequently used to visualize other surfaces such as air pressure or precipitation on weather maps, air quality, and population density. It has been shown that there are inherent perceptual problems in contour interpretation (Griffin and Lock 1979). Contour lines, when compared to other methods of surface representation such as shaded relief, are considered less effective at creating the illusion of three dimensions in the mind of the map-reader (Collier *et al*. 2003). However, one of the primary advantages of contour maps over shaded relief is

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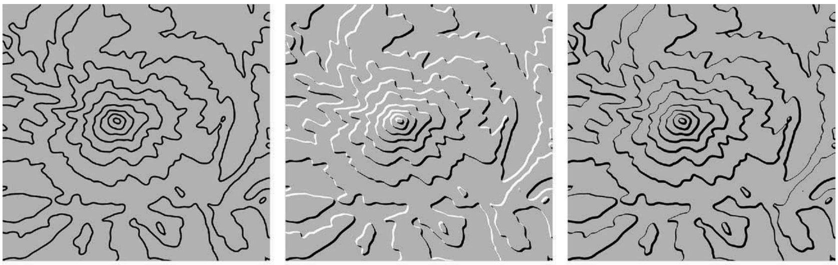


Figure 1. The three types of contour lines in this study (elevation of Mt. Hood, Oregon).

that absolute values of specific locations can be extracted more accurately (Imhof 1982).

The illuminated contour method is a technique that attempts to improve the appearance of the third dimension on contour maps by varying the line width and color of contour lines based on an assumed angle of illumination. Illuminated contour lines are often white on the illuminated side and black on the shadowed side, and have a varying line width that is thinnest at the aspect angle perpendicular to the illumination direction (Figure 1). Shadowed contour lines, as referred to in this study, are another type of contour line that is monochrome and has a varying line width that is thickest on the shadowed side and thinnest on the illuminated side (Figure 1).

While there have been several studies comparing the effectiveness of conventional contour lines to other forms of relief representation (Phillips *et al*. 1975, Potash *et al*. 1978, Wheate 1979), the potential benefits of the illuminated and shadowed contour techniques for improving interpretation of contour maps have not been studied (MacEachren 2004, p. 147). Additionally, modern cartographic and GIS software packages lack the ability to quickly and easily create customized illuminated contour lines. Semi-automated creation of illuminated contour lines from a digital elevation model using GIS and image-editing software is a time-consuming, multi-step process (McGrath 2009).

The two primary reasons illuminated and shadowed contour lines are not widely used today are: (1) a lack of sufficient evidence documenting the benefits of using these methods; and (2) the absence of easily accessible computer-based cartographic tools for creating them. The primary goal of this study is to test whether illuminated and shadowed contour lines provide any benefit to map-readers. A user study with 400 participants was conducted to empirically evaluate the effectiveness of illuminated and shadowed contour lines compared to conventional contour lines and shaded relief. A second goal is to improve existing algorithms for creating illuminated and shadowed contour lines from digital grid data. In order to create these types of contour lines, we developed a specialized, free and open source cartographic software package that allows mapmakers to easily create customized illuminated and shadowed contour lines that can vary width and color based on a variety of parameters (available at http://terraincartography.com/PyramidShader/).

2. Literature review

Illuminated and shadowed contour lines appear on maps dating back to the mid-nineteenth century and the time of manual cartography. Mathematical models and computer-based algorithms that define the variation in line width and color in illuminated contour lines based on aspect and slope have been proposed. Several user studies have looked at how map-readers perceive and interpret conventional contour lines and other forms of relief representation.

2.1. *Historical use of illuminated and shadowed contour lines*

To manually vary line width, cartographers used a calligraphy style pen, allowing them to adjust the width of the line based on the angle of the pen stroke. However, this was a tedious process and complicated the normal contour line drawing technique (Tanaka 1950). Because there were no defined standards for how best to draw illuminated and shadowed contour lines, styles varied widely and would even appear inconsistent within a single map.

The earliest known examples of varying line width based on aspect show subtle variations in width of monochrome contour lines to simulate the appearance of illumination and shadows. In 1845, Michaelis published a map of dense shadowed contour lines with intervals varying by height (Figure 2 left) (Michaelis 1845, Kretschmer 1986). According to Steinhauser (1858), Myrbach von Rheinfeld published an anonymous copper engraving in 1841 with a similar technique. The Swiss Alpine Club used shadowed contour lines in an alpine excursions map in 1865 to enhance the effect of the shaded relief (Leuzinger 1865, Imhof 1982). Randegger (188-) produced a map with pronounced shadowed contour lines in the 1880s; variations of width were very strong locally, but the variation was inconsistent within the map (Figure 2 right). The subtle variation of contour line width is still used today in maps produced by the Swiss national mapping agency to complement the shading of the terrain in areas covered by rocks (Jenny *et al*. 2014).

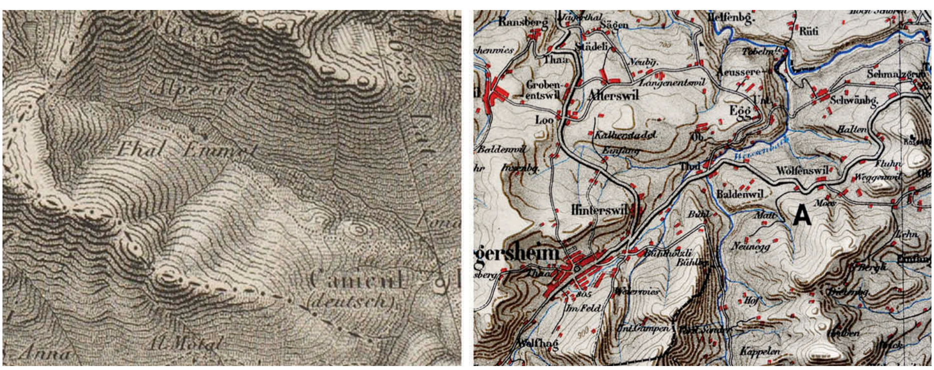


Figure 2. Early shadowed contour line examples. Left: Section of 'Passage du Splügen et de la Via Mala' by E. H. Michaelis (1845) with variable contour interval. Right: Section of 'Wandkarte des Kantons Thurgau' by J. Randegger (188-).

The earliest map examples known to the authors of illuminated contour lines that use white and black contour lines based on terrain orientation were produced by the British Ordnance Survey. An 1858 Scotland sheet map and a 1867 map series on the Thames basin and English Lake District have illuminated contour lines combined with grayscale-layered hypsometric tints (Raisz 1938, Nicholson 1991). Pauliny created hand-drawn illuminated contour maps in the 1890s with an assumed illumination from the west and contour lines that varied from solid to dashed to dotted (Figure 3 left) (Pauliny 1891, 1895, Penck 1903). For additional early examples of the use of illuminated and shadowed contour lines, see Steinhauser (1858), Peucker (1898, p. 65ff), Lössl (1879), and Eckert (1921, p. 611ff), although this is not a comprehensive list of all early maps using this style.

An alternative method to drawing illuminated contour lines is to construct and photograph a three-dimensional contour model. In 1885, Köpcke glued paper maps onto cardboard, cut along the contour lines, stacked the pieces to create a layered relief model, illuminated the model, and took a photograph. Köpcke reproduced the photograph to create illuminated contour maps (Figure 3 right) (Köpcke 1885). Eckert (1921, p. 612) notes an earlier attempt at this technique was carried out by French cartographer Bardin, but he indicated that this attempt was not as successful as Köpcke's.

2.2. *Illuminated contour line algorithms*

A 'relief contour method' was further developed by Tanaka (1950), who was the first to define mathematical principles for the creation of illuminated contour lines. Tanaka's method varies line width and alternates between black and white contour lines based on the azimuthal angle of illumination and the aspect of the terrain. Tanaka defined the width of the contour line as the cosine of the angle between the aspect and the azimuthal angle of illumination. The contour line is thickest at 0 and 180 degrees and thinnest at ±90 degrees to the azimuthal angle of illumination. The line is white, or illuminated, if the aspect of the terrain is within 90 degrees of the azimuthal angle of illumination and black, or shadowed, otherwise. While Tanaka defined the mathematical

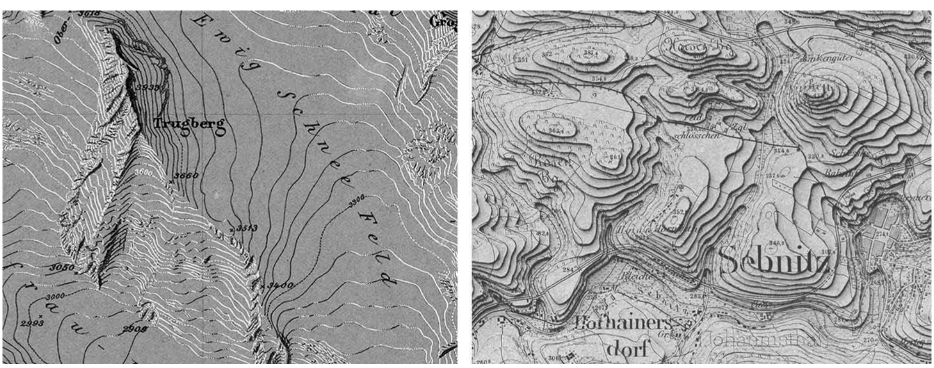


Figure 3. Left: Illuminated contour lines on a manuscript map by Pauliny (1891). Right: Shadowed contour line map created by photographing a three-dimensional cardboard contour model (section of 'Relief-Photogramm Section Sebnitz', 1:50,000, Dresden: Römmler & Jonas).

principle for illuminated contour lines, he still used a calligraphy pen to manually draw all of the lines. A photomechanical method using masks to separate the illuminated and shadowed sides was later proposed to accelerate the production (Gilman 1973, 1981).

Computer-based methods were eventually developed to automate the process of producing illuminated contour lines. Peucker *et al*. (1974) first published a vector-based algorithm and computer implementation of Tanaka contour lines in 1974. The process of creating shadowed contour lines was automated using a computer and pen plotter. To create variable line widths, the lines were plotted several times with a fixed-width pen. Each time the lines were drawn, an offset was applied in the direction of illumination (Peucker *et al*. 1974, Yoeli 1983). Eyton (1984) developed a raster-based contouring algorithm to automatically create illuminated contour lines using a digital elevation model, although contour lines only alternated between black and white and width was not varied. These methods have not been included in modern cartographic and GIS software and are not easily accessible to cartographers.

Illuminated contours can also be created within GIS software. Using scripts in GIS software, Kennelly and Kimerling (2001) modified Tanaka's method by varying line width based on slope and the surface normal in addition to aspect. In Kennelly and Kimerling's (2001) modified method, contour lines falling on steeper slopes are thicker in order to decrease the terraced effect of the illuminated contours' overall appearance. Other modifications to the illuminated contour method proposed by Kennelly and Kimerling (2001) include applying colors to the contour lines based on elevation and using shades of gray to reduce the stark contrast at the black–white transition.

2.3. *Contour line user studies*

User studies about contour lines have primarily focused on how map-readers perceive terrain on a contour map or how conventional contour lines compare to other types of relief representation. Only a limited amount of research has investigated illuminated and shadowed contour lines or other variations of contour maps.

Phillips *et al*. (1975) conducted a between-subjects study with 179 participants comparing the performance of contour lines, relief shading, layer tints, and spot heights and found that contour lines performed equally as well as shaded relief for assessing relative and absolute height differences. The participants were all male police cadets, 16 to 18-years-old, who had been trained on reading contour lines. A similar study on elementary-age children by Filippakopoulou (1998) also found little difference in interpreting contour lines and shaded relief and revealed that children with no prior knowledge of contour lines were able to successfully answer questions about contour maps after listening to a short definition. Another study by Wheate (1979) comparing shaded relief and contour lines showed that shaded relief did give an advantage for both accuracy and speed over contour lines for interpreting major features of the landscape. However, the advantage was significantly reduced and results for the two map types were similar when a more detailed inspection of the map was required. Potash *et al*. (1978) compared maps with only contour lines to those with contour lines and layer tints and those with contour lines and shaded relief. The participants were 48 male army officers who were experienced in using contour maps for land navigation. Results showed that the addition of layer tints to contour lines increased map-reading speed significantly while the addition of shaded relief to contour lines did not increase map-reading speed, but actually decreased accuracy in some cases. The results of these studies are contradicting and indicate that comparing methods of relief representation can be dependent on study design, choice of map-reading task, and type of participant.

It is often assumed that a three-dimensional visualization of an area is needed for accurate terrain interpretation. A study of children, aged 11–12, by Dutton (1978) found that contour map instruction was significantly improved through the use of a three-dimensional model. A similar study with 12–13-year-old students by Angier (1992) found no difference in learning ability between traditional contour map instruction and the use of three-dimensional relief models. A study of high school and college-aged students by Griffin and Lock (1979) found inherent perceptual problems when identifying slope on contour maps. Lanca (1998) compared male and female college students using contour maps and three-dimensional land surface drawings of an area to determine how terrain visualization relates to contour map reading ability. It was found that while males were better at recognizing the land surface that corresponded to the contour map, there were no gender differences in the contour map-reading tests. The conflicting results of these studies suggest that the methods of learning and interpreting contour maps are not yet fully understood and vary between individuals.

Another between-subjects study by Phillips (1979) with 87 undergraduate student participants compared conventional contour lines to 'wedding cake' contour lines, which use double lines on the shadowed side to convey the direction of slope. The study found no difference in performance between the two types of contour lines. Phillips noted that it is possible that the failure to reach statistical significance could be due to testing insufficient subjects. DiBiase *et al.* (1994) compared statistical surfaces represented by standard isolines, shadowed isolines, and weighted isolines – where line width varies in proportion to data values – and found improved accuracy and speed for weighted isoline interpretation, but little difference between standard and shadowed isolines. Morita (2001) used illuminated contour lines in a user study that recorded participants' eye movements as they looked at representations of convex and concave abstract geometric forms. It was determined that participants were able to make a distinction between concave and convex objects, although it is unclear how this may translate to more complex forms on actual contour maps.

A user study with 70 undergraduate and graduate geography students by Wheate (1979) compared performance and search time results of shaded relief, Tanaka contour lines, conventional contour lines, and maps without relief representation. The map-reading tasks were highly varied and results between map types were inconsistent. Search times and performance results between Tanaka and conventional contour maps were nearly equal with map-reading tasks involving hydrographic targets. In tasks involving the location of spot heights, significant differences were found between Tanaka and conventional contour lines for points on eastern slopes for one map area and for eastern and western slopes for another map area; however, no significant differences were found for either map area for locating points in valleys and on hilltops (Wheate 1979).

In summary, only a few user studies have compared illuminated contour lines or variations of the illuminated contour method to conventional contour lines (Phillips 1979, Wheate 1979). Results of these studies have been inconsistent, showing no significance for some map-reading tasks and significance for others. There have not been any user studies focused specifically on comparing the accuracy and map-reading speed of illuminated and shadowed contour lines with conventional contour lines in a within-subjects design.

3. Methods

3.1. *User study design*

A user study compared four map types: illuminated contour lines, shadowed contour lines, conventional contour lines, and shaded relief. The user survey consisted of a brief tutorial, a series of two main question types involving map-reading tasks, and a demographic and map preference survey. Using a within-subjects design, all participants answered questions about all map types in a randomized order to minimize learning effects.

Participants for the study were recruited through Mechanical Turk, a web-based crowdsourcing tool developed by Amazon to allow study participants to complete small tasks, referred to as Human Intelligence Tasks, for micro-payments. Mechanical Turk has been shown to be an effective method for visualization design studies, producing similar results to more traditional laboratory-based studies (Mason and Watts 2009, Heer and Bostock 2010, Kosara and Ziemkiewicz 2010). Participants were directed to an online questionnaire to complete the study, compensated $1.00, and allowed to complete the study only once.

An introductory tutorial included definitions of contour lines and shaded relief, and showed basic examples of the four map types. This was done to ensure participants had at least a basic understanding of contour lines before beginning the study. Illuminated and shadowed contours were shown as alternative forms of contour lines, but the nature and principles of illuminated and shadowed contour lines were not explained in the tutorial. A three-dimensional image of terrain with contour lines was shown at various oblique angles. Examples of the two question types and instructions were included.

The first question type analyzed how relative height differences were perceived. Study participants were asked to select the higher of two markers randomly placed on the map. This type of elevation comparison task has been used in previous map studies (Phillips *et al*. 1975, Potash *et al*. 1978, Willett *et al*. 2015) and is an indicator of how well a map-reader is interpreting variation in values on a map. There were ten questions for each map type and a time limit of ten seconds for each question. Within a set of ten questions for a given map type, the map extent did not change. All study participants saw the same maps, although the order of map types was randomized for each participant. Every fifth contour line in the three contour map types was labeled with the height value (Figure 4 left).

The second question type asked participants to click on the location they perceived as being the highest point on the map. There was a time limit of 20 seconds for each question and a total of 12 questions, each of a different location, with randomized map types. Contour labels identifying the actual elevation values were excluded on the illuminated and shadowed contour maps in the second question type in order to assess

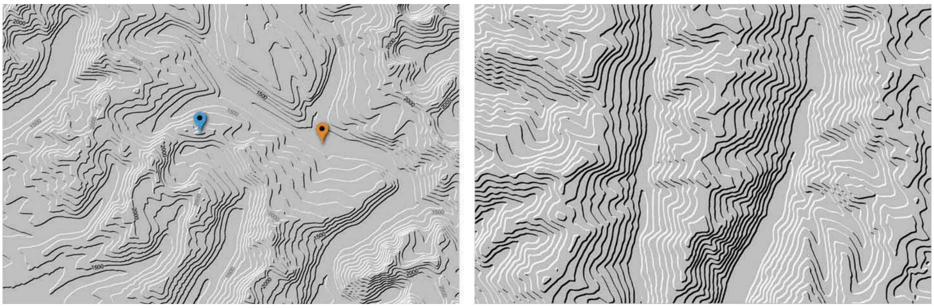


Figure 4. Examples of the two question types used in the user study – relative height question (left) and maximum height question (right).

the ability of map-readers to perceive the third-dimension without reading labels (Figure 4 right).

Cartographers use shaded relief and contour lines for different purposes. The grays-cale gradients of a shaded relief effectively provide information about the three-dimensionality of a terrain, whereas contour lines (including shadowed and illuminated contour lines) are designed to show elevation and to allow the reader to extract elevation values. Contour lines can also convey the third dimension of landforms, but are considerably less effective than shaded relief at doing so (Imhof 1982, Collier *et al.* 2003). Consequently, we expect the three variants of contour lines to outperform shaded relief in our user study, because users are asked to identify the higher of two points or to locate the highest point in a map. To evaluate the perceived effectiveness of the four different techniques for the representation of the three-dimensionality of the terrain, the demographic and map preferences section additionally included the following Likert scale question: 'Rate the map based on your agreement to the following statement. This map shows variations in elevation well and produces an appearance of the third dimension.' Participants could select between 'strongly agree', 'agree', 'neither agree nor disagree', 'disagree', or 'strongly disagree'. Additional questions gathered information about gender, age, education, topographic map reading experience, and participants' self-evaluated ability to read a topographic map with contour lines.

3.2. *Contouring algorithm*

In order to create illuminated and shadowed contour maps for the user study, a raster-based contouring algorithm was integrated into a specialized cartographic software package. The contouring algorithm is an extension of previous work (Saito and Takahashi 1990) and allows mapmakers to customize and create new variations of illuminated and shadowed contour lines in addition to the Tanaka contouring method. Contour lines are calculated from a raster surface. A raster-based method, rather than a method based on vector lines, is used which allows for continuously varying line widths and smooth color gradients based on local changes of slope and aspect.

For each pixel, the algorithm determines whether the pixel is drawn as a contour line. The parameters include the slope s at the pixel, the desired width w of the contour line, and the height distance z from the pixel to the nearest contour interval. The height

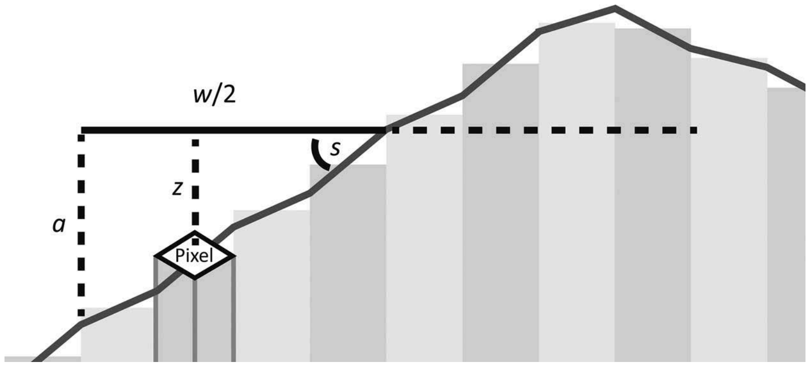


Figure 5. Cross section of a grid surface showing the basis of contouring algorithm calculation.

difference a from the center of the contour line to the point on the surface located at the edge of the contour line can be calculated using Equation (1) (Saito and Takahashi 1990) (Figure 5).

$$a = \tan(s) \cdot \frac{w}{2} \tag{1}$$

If the height difference z is smaller than the height difference a, then the pixel is on a contour line; otherwise, the pixel is not. This method is based on the assumption that the slope angle s is constant for all pixels between the pixel and the nearest contour interval. In Equation (1), the contour line width w is constant, which results in conventional contour lines (Figure 6a).

The variation of brightness of the contour line is based on the azimuthal angle of illumination, aspect α (the azimuthal direction a slope faces), and the transition angle t, the angle relative to the azimuthal angle of illumination at which contour lines change from black to white. If the difference d between the azimuthal angle of illumination and the aspect α of the pixel is less than the transition angle t, the pixel is white; otherwise it is black ($t = \frac{\pi}{2}$ for the Tanaka method). This results in contour lines with constant width in black and white colors (Figure 6b), which are equivalent to those created by Eyton (1984).

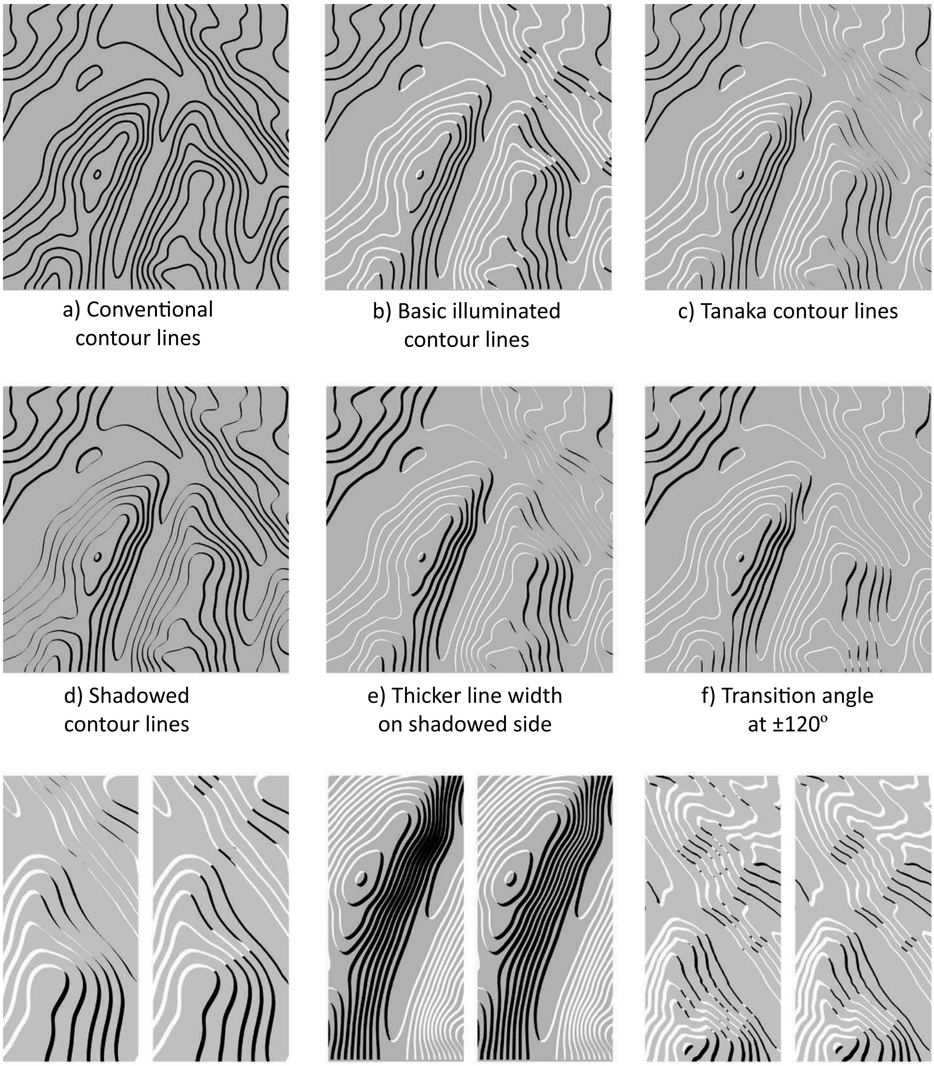
The width w in Equation (1) can be modulated with the cosine function to create illuminated contour lines with a varying width w_i (Figure 6c). The width w_i is calculated using Equation (2) (Tanaka 1950) and replaces w in Equation (1).

$$w_i = w \cdot cos(d) \tag{2}$$

The modulated width w_s of shadowed contour lines (*i.e.* usually black-only contour lines) is based on the sine function instead of the cosine function (Figure 6d):

$$w_s = w \cdot \sin\left(\frac{d}{2}\right) \tag{3}$$

The software user can independently vary the width of the shadowed and illuminated side of illuminated contour lines by assigning scaling factors to the width w (Equation (4),



a) Conventional contour lines

b) Basic illuminated contour lines

c) Tanaka contour lines

d) Shadowed contour lines

e) Thicker line width on shadowed side

f) Transition angle at ±120º

g) Minimum line width

h) Minimum distance between contour lines

i) Despeckle

Figure 6. Steps in the computation of illuminated and shadowed contour lines.

Figure 6e). Similarly, the transition angle t can also be varied and the difference d between the azimuthal angle of illumination and the aspect needs to be adjusted accordingly. The adjustment is made by scaling d based on the relationship of the new transition angle t to the initial transition angle value of $\frac{\pi}{2}$ (Equation (4), Figure 6f).

For the illuminated side $(d < t)$: $w' = w \cdot f_i$

$$d' = \frac{d}{t} \cdot \frac{\pi}{2} \tag{4}$$

For the shadowed side $(d \geq t)$: $w' = w \cdot f_s$

$$d' = \left(\frac{d-t}{\pi-t}\cdot\frac{\pi}{2}\right) + \frac{\pi}{2}$$

In Equation (4), f_i is the scaling factor for the illuminated width and f_s is the scaling factor for the shadowed width. The scaled width w' and difference d' replace w and d in Equation (2).

While the width of contour lines in the Tanaka method reaches 0 at the transition angle, a minimum width $w_{\min}$ can be applied to w_i and w_s to enforce a continuous line with a minimum width $w_{\min}$ (Figure 6g):

$$w_i^{'} = \max(w_{\min}, w_i)\text{ and }w_s^{'} = \max(w_{\min}, w_s) \tag{5}$$

Depending on the contour interval, contour lines can coalesce into each other in areas of steep slopes, resulting in unattractive blotches on the map where it is impossible to differentiate height values. A minimum distance between contour lines can be achieved by restricting line width based on slope. The minimum distance between two lines is $d_{\min}$, the slope (as a percentage) is $s_{[\%]}$, and i is the contour interval. The corresponding maximum line width $w_{\max}$ is

$$w_{\max} = \frac{i}{s_{[\%]}} - \frac{d_{\min}}{2} \tag{6}$$

The adjusted widths $w_i^{''}$ and $w_s^{''}$ for the illuminated and shadowed sides are defined in Equation (7) and replace w in Equation (1) (Figure 6h).

$$w_i^{''} = \min\left(w_{\max}, w_i^{'}\right)\text{ and }w_s^{''} = \min\left(w_{\max}, w_s^{'}\right) \tag{7}$$

When the aspect of a contour line varies extensively around the transition angle, the line can change between white and black many times within a short distance, which may not be a desirable effect. Applying a Gaussian low-pass filter to the grid surface before computing the aspect angle can reduce this abrupt change. The low-pass filter is applied only to the computation of terrain aspect and does not affect the computation of slope, which is used in Equation (1). The low-pass filtered grid is used to compute terrain aspect α', which replaces α in the computation of d (used in Equations (2)–(4)). The amount of low-pass filtering is controlled by a parameter referred to as 'despeckle' in the software (Figure 6i).

For illuminated contour lines, a color gradient can be applied between the illuminated and shadowed contour lines by linearly interpolating between the color for illuminated contour lines and the color for shadowed contour lines. The color interpolation is applied within an angle around the transition angle. This method can be problematic when the interpolated colors match the background color (Kennelly and Kimerling 2001). For example, white and black lines will interpolate to shades of gray and disappear into a gray background.

The contour lines can be made to appear smoother by using a pixel size that is considerably smaller than the cell size of the surface model and by applying anti-aliasing (Geisthövel 2003). We achieve anti-aliasing by applying partial transparency on pixels along the borders of contour lines. The smoothstep function, an s-shaped cubic Hermite interpolation curve commonly used in computer graphics, is applied to the alpha values along the edges of the contour lines to achieve this effect.

The described contouring algorithm is integrated into Pyramid Shader, a free and open source software package available at http://terraincartography.com/PyramidShader/.

3.3. *Contour map creation*

All maps used in the study were created using the algorithm described in the preceding section. The extents of each map were equal within each question type and had a contour interval of 100 unspecified units. Every fifth contour line on the conventional contour maps was labeled and represented with a thicker line. These index contour lines are commonly used in conventional contour maps. Anti-aliasing was applied to the created contour lines, and maps were sized to 900 × 600 pixels and presented at screen resolution (Figure 7).

Illuminated contour lines were created with a minimum to maximum line width ratio of 1:4, a transition angle of 90°, and a moderate level of despeckling. With the chosen interval, none of the contour lines touched. Shadowed contour lines had a minimum to maximum line width ratio of 1:4. The conventional contours had a standard contour line to index contour line width ratio of 1:3. The azimuthal angle of illumination for all relevant map types is from the northwest.

The map locations used for the first question type represent four mountainous areas of equal extent within Glacier National Park, Montana, USA. The map locations used for

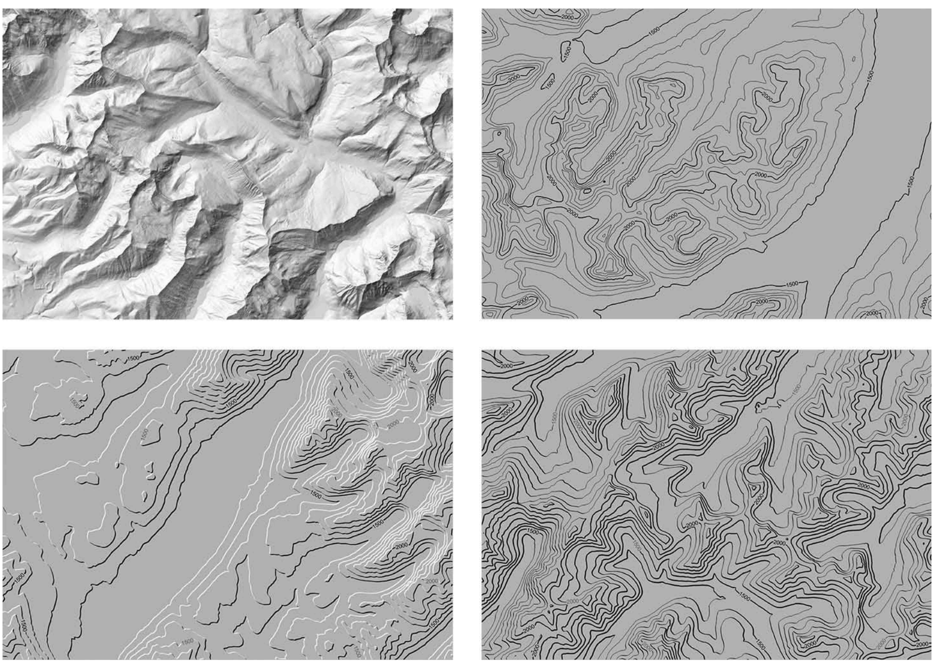


Figure 7. The four map types and locations used for the relative height questions in the user study. Top left: shaded relief; top right: conventional contour lines; bottom left: illuminated contour lines; bottom right: shadowed contour lines.

the second question type represent twelve mountainous areas of equal extent in Ticino, Switzerland. Participants were not informed about the location of the maps.

3.4. *Statistical methods*

The four main groups of data obtained from the user study were analyzed separately. McNemar's test (McNemar 1969) was used to analyze differences between pairs for the results of the relative height question, which were in binary right–wrong format. This is a non-parametric test similar to a chi-square test that is used for repeated measures and binary data (Motulsky 2014). Results were summed and the total number of correct answers for each map type was tested for significant differences for all possible combinations of map type pairs. A significant difference is found if the chi-square value is greater than the chi-square critical value.

The other three groups of data consisted of continuous, measured data. The results of the maximum height question were scored by taking the elevation of the participant's click as a percentage of the range of all possible elevation values. For the timing results from both question types and the results from the maximum height question, averages by participant for each map type were analyzed. Wilcoxon signed-ranks test, a non-parametric test appropriate for paired data when *t*-test assumptions such as normal distribution cannot be met, was used to test all possible combinations of pairs (McCrum-Gardner 2008, Motulsky 2014). Because of the large sample size, an effect size calculation was made to clarify the effect of the significant differences in the Wilcoxon signed-rank's test. Cohen's r (Cohen 2013) was calculated and the effect was considered large for 0.5, medium for 0.3, and small for 0.1 (Fritz *et al*. 2012). A significance level of 0.01 was used for all statistical tests in this user study.

4. User study results and discussion

There were a total of 455 participants in the user study. Results where participants failed to answer at least 90% of the timed questions for each map type, possibly due to connection problems or other issues, were discarded. A total of 397 user study results were used in the statistical analysis. The remaining unanswered questions in the first question type were scored as incorrect. The unanswered questions in the second question type, where there was not an inherent correct or incorrect answer, were discarded. The average completion time for the study was 18 minutes, with a minimum of 5 minutes, a maximum of 64 minutes, and a standard deviation of 8 minutes.

4.1. *Relative height question*

For the relative height questions, which asked participants to select the higher of two markers, the total number of correct answers was used in a pairwise comparison for each map type. The percentage of correct answers was highest for the illuminated contour maps (90.1% correct answers) (Table 1). The illuminated contour maps were significantly different than all other map types according to McNemar's test, with χ^2-values being larger than the critical χ^2-value (Table 2). There were no other significant differences between pairs of map types.

Table 1. Raw results for the relative height question (n = 3970 for each map type). Because there were only two answer options, complete randomness is 50% correct.

Map type	Percent correct (%)	Mean timing (seconds)	Std dev timing
Illuminated	90.1	3.0	1.3
Shadowed	85.5	3.4	1.5
Conventional	83.4	3.6	1.6
Shaded relief	81.9	2.5	1.1

Table 2. McNemar's test results for the relative height question, χ^2-crit = 3.8.

Map type pairs	χ^2	Sig
Illuminated – shadowed	4.7	Yes
Illuminated – conventional	10.1	Yes
Illuminated – shaded relief	15.2	Yes
Shadowed – conventional	1.0	No
Shadowed – shaded relief	3.0	No
Shaded relief – conventional	0.5	No

Results were also organized as a percentage of correct answers for each map type for every participant. The number of participants who answered all ten questions correctly was about twice as high for illuminated contour maps at 200 participants, or 50.4%, compared to conventional contour maps at 110 participants, or 27.7%, and shaded relief maps at 96 participants, or 24.2% (Figure 8).

Based on these measures, study participants were able to more accurately answer questions about relative height differences with illuminated contour maps than with other map types. Compared to conventional contour maps, no advantages for shadowed contour maps were shown for distinguishing relative height differences.

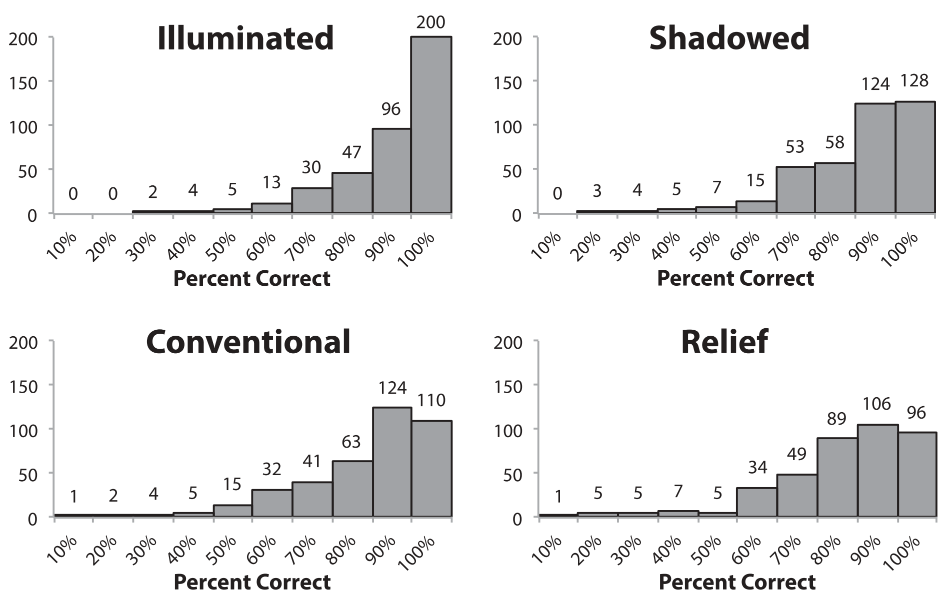


Figure 8. Histograms of the relative height question for illuminated, shadowed, and conventional contour lines, as well as shaded relief; percent correct per participant.

Shaded relief and conventional contour lines were more difficult for the study participants to interpret, with an accuracy of 81.9% correct answers for shaded relief and 83.4% correct answers for conventional contour lines (Table 1).

4.2. *Timing of relative height question*

Results for the length of time it took each participant to answer the relative height questions were organized by participant as an average of each map type. Significant differences were found for each map type pair ($p < 0.01$) (Table 3). Shaded relief questions received the quickest answers at an average of 2.5 seconds, followed by illuminated contour lines at 3.0 seconds, shadowed contour lines at 3.4 seconds, and conventional contour lines at 3.6 seconds (Table 1). While the shaded relief questions were answered the quickest, the results were the least accurate.

An effect size calculation shows a medium significance between illuminated contour lines and conventional contour lines (Table 3). The pairwise tests of effect size between shadowed contour lines and conventional contour lines as well as between shadowed contour lines and illuminated contour lines show a low significance.

Using illuminated contour maps, participants were able to answer the relative height questions quicker and more accurately than with all other contour map types. While shaded relief questions were answered the quickest overall, answers for the shaded relief map type were the least accurate. Shadowed contour maps provided only a small advantage over conventional contour lines in terms of timing and accuracy.

4.3. *Maximum height question*

The results of the maximum height questions, where participants had to click on the location they thought was the highest location, were summarized as an average score per participant for each map type. The mean scores for unlabeled illuminated contour lines (79.5%) and labeled conventional contour lines (79.4%) were nearly identical (Table 4). Shadowed contour lines had a mean of 75.3%, while shaded relief had the poorest performance at 69.6%.

No significant difference was found between unlabeled illuminated and labeled conventional contour lines (Table 5). Based on the effect size statistic, there was no significant difference between unlabeled illuminated and unlabeled shadowed contour lines, while there was a significant difference between unlabeled shadowed and labeled conventional contour lines. This indicates that study participants obtained height information from both unlabeled illuminated contour lines as accurately as labeled

Table 3. Cohen's r effect size results for relative height timing. Significance was found for all map type pairs using Wilcoxon signed-ranks test ($p < 0.01$).

Map type pairs	Effect r	Effect size Sig
Illuminated – shadowed	0.23	Low
Illuminated – conventional	0.30	Med
Illuminated – shaded relief	0.34	Med
Shadowed – conventional	0.12	Low
Shadowed – shaded relief	0.46	Med
Shaded relief – conventional	0.49	Med

Table 4. Raw results for the maximum height question.

Map type	Mean accuracy (%)	Std dev (%)	Mean timing (seconds)	Std dev timing
Illuminated, unlabeled	79.5	15.7	6.2	3.6
Shadowed, unlabeled	75.3	20.8	6.1	3.7
Conventional, labeled	79.4	18.1	6.3	3.3
Shaded relief	69.6	19.8	7.9	3.8

Table 5. Wilcoxon signed-ranks test and Cohen's r effect size results for the maximum height question.

Map type pairs	*p*-Value	Sig	Effect r	Effect size sig
Illuminated – shadowed	<0.01	Yes	0.12	Low
Illuminated – conventional	0.741	No	X	X
Illuminated – shaded relief	<0.01	Yes	0.381	Med
Shadowed – conventional	<0.01	Yes	0.127	Low
Shadowed – shaded relief	<0.01	Yes	0.267	Low
Shaded relief – conventional	<0.01	Yes	0.388	Med

conventional contour lines. Shaded relief maps scored significantly lower than all other map types (Table 5).

4.4. *Timing of maximum height question*

Results for the length of time it took for study participants to answer the maximum height questions were organized by participant as an average of each map type. The three contour map types had similar timing results with means between 6.1 and 6.3 seconds (Table 4). No significant differences between contour map types were found. Study participants spent an equal amount of time finding the highest point on the map with unlabeled illuminated and shadowed contour lines as with labeled contour lines. A Wilcoxon signed-ranks test ($p < 0.01$) confirmed that the timing results for answers to shaded relief questions took significantly longer than answers to contour line questions.

These timing results indicate that participants were able to interpret height variation in the same amount of time on the unlabeled illuminated and shadowed contour maps as well as labeled conventional contour maps. This could indicate that illuminated contour maps made with fewer contour labels could be read as quickly and accurately as conventional contour lines with more labeled index contour lines. It is clear that the shaded relief maps are not suitable for quickly and accurately locating an absolute elevation value such as maximum height, which is consistent with previous knowledge (Imhof 1982).

4.5. *Three-dimensional appearance*

The Likert scale question, which asked participants to rate each map type based on their agreement to the statement it shows variations in elevation well and produces an appearance of the third-dimension, revealed that nearly as many participants responded positively (agree or strongly agree) to the illuminated contour maps (83.8%) as the

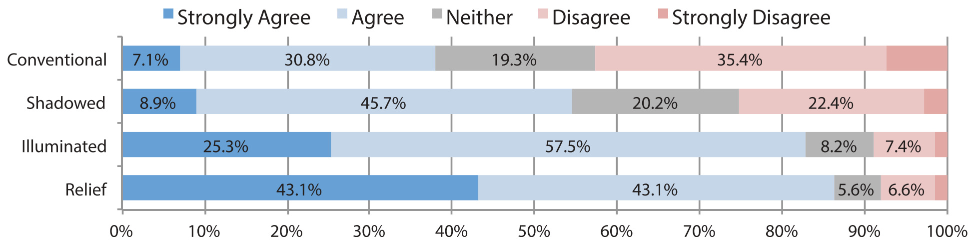


Figure 9. Participants' views on the statement that each map type shows variations in elevation well and produces an appearance of a three-dimensional space.

shaded relief maps (86.2%) (Figure 9). The shadowed contour maps received positive responses from 54.6% of participants while the conventional contour map received positive responses from 37.9% of participants.

4.6. *Demographics*

Of the 397 participants, 327 were from the United States, 50 were from India, and 20 were from other countries. The number of correct responses for all questions and map types was approximately 10% lower for participants outside of the United States, although the relative differences between map types were similar. There were 200 male and 197 female participants and no significant differences between the results of each were found based on gender.

Results between participants with a bachelor's degree or higher (n = 213) were compared with those without a bachelor's degree (n = 183). Participants without a bachelor's degree performed slightly better on all four map types than those with a bachelor's degree, but differences were not significant. Participants who self-rated their topographic map-reading ability as good or very good (n = 219) were compared to those who self-rated as neutral or bad (n = 178) and no significant differences were found. It is interesting to note that the results of those who self-rated as neutral or bad performed slightly better at interpreting illuminated and conventional contour lines than those who self-rated as good or very good.

None of the participants reported using contour maps on a daily basis. Only two participants claimed to use contour maps a few times per week, while 16 used them a few times per month, and 124 used them a few times per year. A total of 253 participants reported that they never use topographic maps with contour lines.

5. Conclusion

For elevation comparison tasks, study participants were faster and more often extracted correct elevations when using illuminated contour lines compared to conventional contour lines. To a lesser extent, study participants showed an improved map reading speed for elevation comparison tasks when using shadowed contour lines compared to conventional contour lines. Study participants were able to identify maximum height values using unlabeled illuminated contour maps with equal accuracy and speed as labeled conventional contour maps. In line with previous studies, relative and absolute height identification from shaded relief was less accurate than with all contour map types. However, participants answered the relative height questions on the shaded relief maps quicker than all other map types, possibly indicating that shaded relief instilled a false sense of confidence in participants and misrepresented the terrain for this type of analysis.

A contouring algorithm with new elements has been presented. The creation of customized contour lines has been automated, which reduces the amount of time required to generate illuminated and shadowed contour maps previously produced manually or as a multi-step digital process.

One of the limitations to using illuminated contour lines is the requirement of a background that contrasts with both the illuminated and shadowed contour line colors. As a result, detailed maps with many additional map elements may not be suitable for white and black contour lines. Another limitation of illuminated and shadowed contour lines is that they cover more space than conventional contour lines. They also require a larger interval than conventional contour lines to avoid too dense or touching lines in areas of steep slopes. The presented method can impose a minimum distance between contour lines by thinning contour lines.

Future work is needed to test the effectiveness of different variations and more subtle implementations of the illuminated contour method. For example, bathymetric maps,

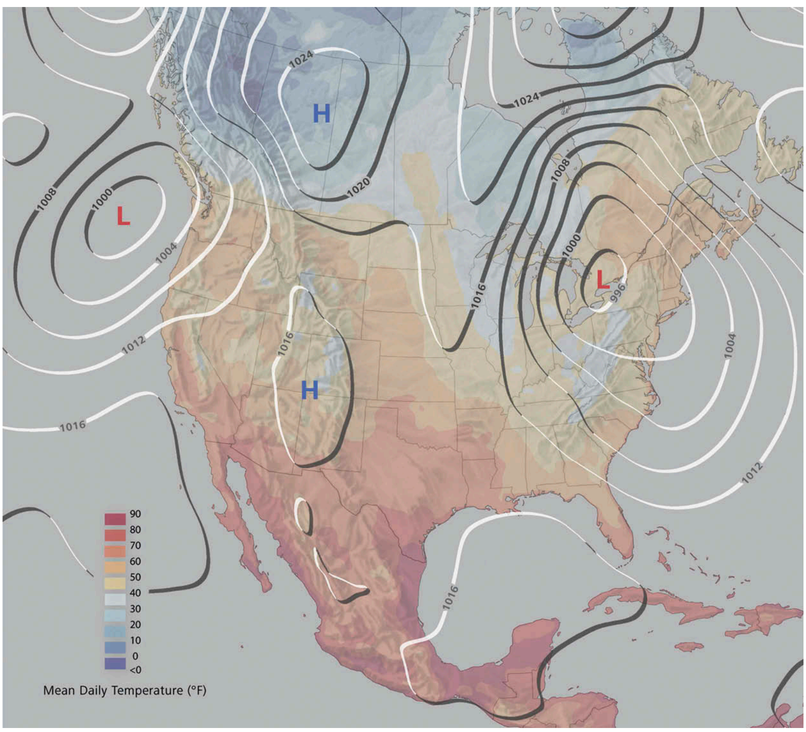


Figure 10. Multivariate weather map showing air pressure represented by illuminated contour lines and temperature represented by layer tints (Hurricane Sandy, 30 October 2012).

which typically have fewer map elements than topographic maps, may benefit from the use of illuminated contour lines. Futures studies could additionally compare illuminated and shadowed contour lines to maps that combine shaded relief with hypsometric tints, or shaded relief with conventional contours.

Although the contour maps in this study were created using elevation data, the illuminated contour method can be applied to other statistical surfaces. For instance, Figure 10 is a multivariate weather map showing daily average temperature and air pressure for North America after Hurricane Sandy made landfall in October 2012. Adhering to weather map standards, mean sea level atmospheric pressure is represented by isolines and temperature is represented by layer tints. In this example, however, isolines are represented as illuminated contour lines instead of conventional contour lines. Elevation is shown as shaded relief. Based on the results in this study, this map shows areas of low and high pressure in a more effective way than a traditional weather map that uses conventional isolines.

Acknowledgements

The authors would like to thank Dr. Richard Oliver for his expertise on historical British Ordnance Survey maps, Dr. Lorenz Hurni (Institute of Cartography and Geoinformation, ETH Zürich) for providing scans of various maps, Markus Oehrli (Zentralbibliothek Zürich), Dr. Tom Klöti (swisstopo) and Dr. Martin Rickenbacher (swisstopo) for their help in finding maps, Tom Patterson (US National Park Service) and Dr. Thomas Pingel (Northern Illinois University) for their advice and support early on in this project. The authors also thank the anonymous reviewers for their valuable comments.

Disclosure statement

No potential conflict of interest was reported by the authors.

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