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Title: Evaluating the Effectiveness of Illuminated and Shadowed Contour Lines

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Bernhard J. Jenny

Illuminated contour lines, where line width and color are varied based on an angle of illumination, date back to the mid-nineteenth century, but their effectiveness compared to conventional contour lines has not been fully examined. Currently, illuminated contour lines are not widely used in computer-based cartography because they are not included in most GIS and mapmaking 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 contour maps. A user study comparing illuminated contour lines to other relief representation techniques with 400 participants was conducted. The 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 timing. These findings suggest that illuminated contour lines could be used more frequently for improved visualization of terrain and other surface data on maps.

Evaluating the Effectiveness of Illuminated and Shadowed Contour Lines

by
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APPROVED:

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James D. Eynard, Author

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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) and contour lines, when compared to other methods of surface representation, 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 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 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).

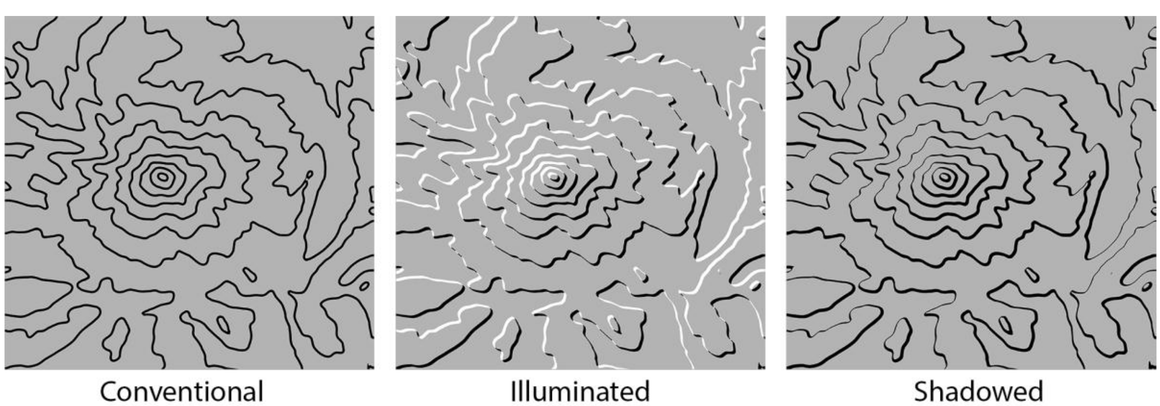

Figure 1. The three types of contour lines in this study (elevation of Mt. Hood, Oregon).

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 technique for improving interpretation of contour maps has 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 this technique is not widely used today are: (1) a lack of sufficient evidence documenting the benefits of using illuminated and shadowed contour lines; and (2) the absence of easily accessible computer-based cartographic tools for creating illuminated and shadowed contour lines. The 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. Results of the user study indicate that the illuminated contour method is advantageous for interpreting terrain quickly and accurately. In order to create these types of maps, 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.

2. Literature Review

Illuminated 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 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 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 created a map of dense shadowed contour lines with intervals varying by height (Figure 2) (Kretschmer 1986, Michaelis 1845). 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 (Imhof 1982, Leuzinger 1865). Randegger (188-) produced a map with pronounced shadowed contour lines in the 1880s. Variations of width are very strong locally, but the variation is inconsistent within the map (Figure 2). 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 (Jenny *et al.* 2014).

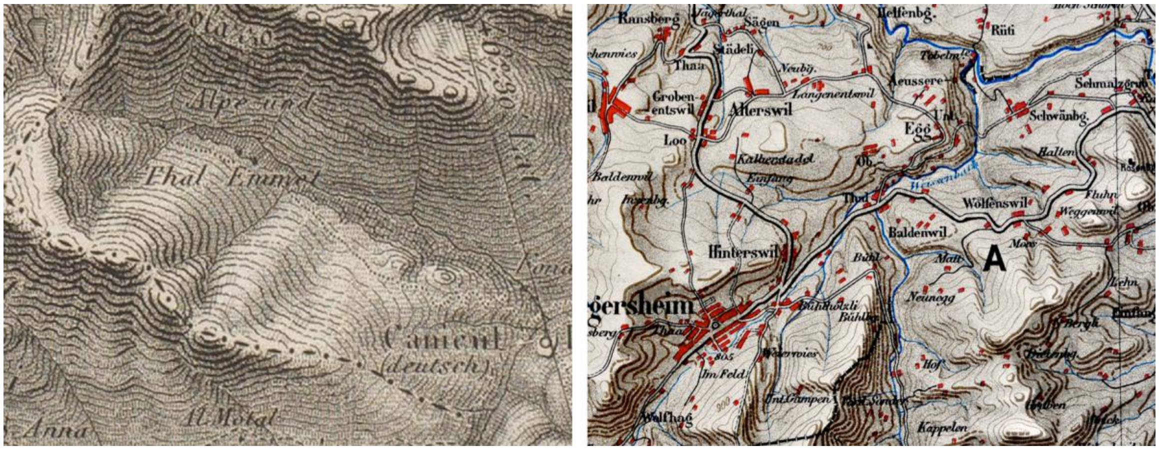

Figure 2. Early shadowed contour line examples. Left: Section of ‘Passage du Splügen et de la Via Mala’ by E. H. Michaelis (1845) with variable contour interval. Right: Section of ‘Wandkarte des Kantons Thurgau’ by J. Randegger (188-).

The earliest map examples known to the author 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 shaded zones of elevation (Nicholson 1991, Raisz 1938). These maps, which were engraved in copper plates, combined illuminated contour lines with grayscale layered hypsometric tints. 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) (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) (Köpcke 1885). Eckert (1921,

p. 612) notes an earlier attempt at this technique was carried out by French cartographer Bardin, but comments that this attempt was not as successful as Köpcke's.

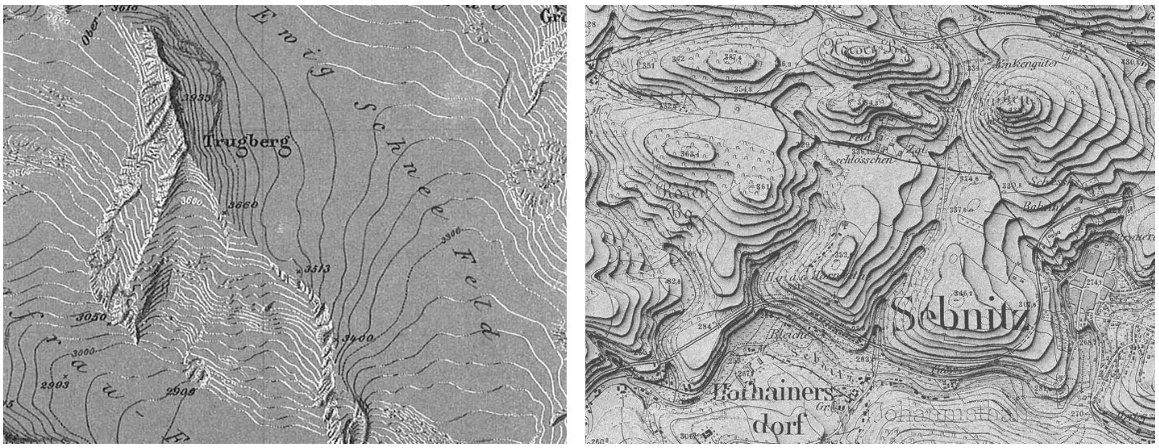

Figure 3. Left: Illuminated contour lines on a manuscript map by Pauliny (1891). Right: Shadowed contour line map created by photographing a three-dimensional cardboard contour model (section of 'Relief-Photogramm Section Sebnitz', 1:50 000, Dresden: Römmler & Jonas).

2.2. Illuminated Contour Line Algorithms

A "relief contour method" was further developed by Tanaka, who was the first to define mathematical principles for the creation of illuminated contour lines (Tanaka 1950). Tanaka's method varies line width and alternates between black and white contour lines based on the 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 angle of illumination. The contour line is thickest at 0 and 180 degrees and thinnest at ±90 degrees to the angle of illumination. The line is white, or illuminated, if the aspect of the terrain is within 90 degrees of the angle of illumination and black, or shadowed, otherwise. While Tanaka defined the mathematical 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. A vector-based algorithm and computer implementation of Tanaka contour lines were first published in 1974 (Peucker *et al.* 1974). The process of creating shadowed contour lines was automated using a computer and plotter, which required the lines to be drawn several times at displaced origins to increase line width on the shadowed side (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.

Using scripts in GIS software, Tanaka's method was modified to vary line width based on slope and the surface normal in addition to aspect (Kennelly and Kimerling 2001). The methods described above can also be used to create Tanaka contours within GIS software. 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 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 also found little difference in 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 (Filippakopoulou 1998). Another study 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, but the advantage was significantly reduced when a more detailed inspection of the map was required (Wheate 1979). 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 to 12, found that contour map instruction was significantly improved through the use of a three-dimensional model (Dutton 1978). A similar study with 12 to 13-year-old students found no difference in learning ability between traditional contour map instruction and the use of three-dimensional relief models (Angier 1992). A study of high school and college-aged students found inherent perceptual problems when identifying slope on contour maps (Griffin and Lock 1979). Another study 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 (Lanca 1998). 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 may 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 1979). Phillips notes that it is possible that the failure to reach statistical significance could be due to testing insufficient subjects. A study comparing statistical surfaces represented by standard isolines, shadowed isolines, and weighted isolines—where line width varies in proportion to data values—found improved accuracy and speed for weighted isoline interpretation, but little difference between standard and shadowed isolines (DiBiase *et al.* 1994). Illuminated contour lines were used in a user study that recorded participants’ eye movements as they looked at representations of convex and concave abstract geometric forms (Morita 2001). 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. In 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 (Heer and Bostock 2010, Kosara and Ziemkiewicz 2010, Mason and Watts 2009). Participants were directed to an online questionnaire to complete the study. Participants were compensated $1.00 and were only allowed to complete the study once.

An introductory tutorial included definitions of contour lines and shaded relief, and showed examples of the four map types. 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 location did not change, although the location and the order of map types were randomized for each participant. Every fifth contour line in the three contour map types was labeled with the height value.

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 the ability of map-readers to perceive the third-dimension without reading labels.

The demographic and map preference section included a Likert scale question asking the participants to rate each map type based on their agreement to the statement that it produces an appearance of a three-dimensional space. Additional questions gathered information about gender, age, education, topographic map 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 algorithm is based on previous work (Saito and Takahashi 1990), but allows mapmakers to customize and create new variations of illuminated contour lines in addition to the implementation of the Tanaka contouring method. Contour lines are calculated from a raster surface. A raster-based method, rather than a vector-based method, is used to allow 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 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 4). 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 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 5a).

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

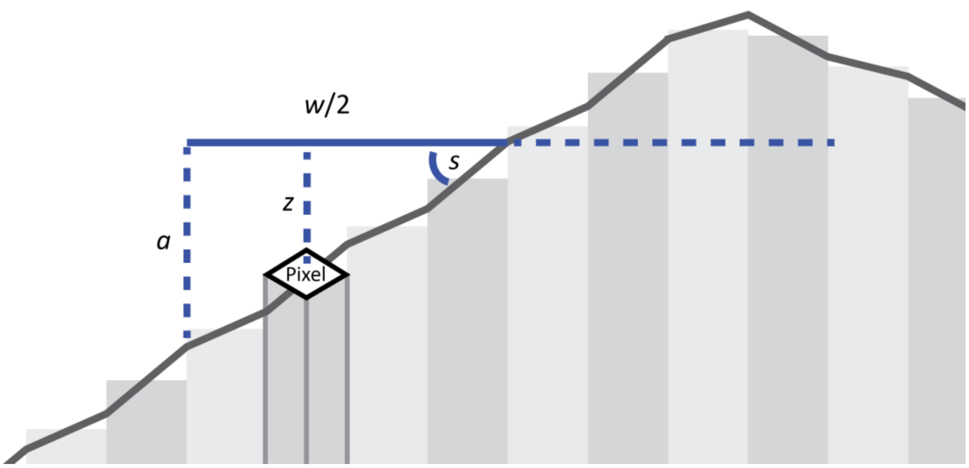

Figure 4. Cross section of a grid surface showing basis of contouring algorithm calculation.

The variation of brightness is based on the azimuthal angle of illumination, aspect (the azimuthal direction a slope faces), and the transition angle t from black to white. If the difference d between the azimuthal angle of illumination and the aspect of the pixel is less than the transition angle t, the pixel is white, otherwise it is black ($t = 90°$ for the Tanaka method). This results in contour lines with constant width in black and white colors (Figure 5b), 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 5c). 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, and does not change color (Figure 5d):

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

The width of the shadowed and illuminated side of illuminated contour lines can be varied independently by assigning scaling factors to the width w (Equation 4, Figure 5e). Similarly, the transition angle t can also be varied and the difference d between the 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 90° (Equation 4, Figure 5f).

For illuminated side ($d < t$):

$$w' = w \cdot f_i$$
$$d' = \frac{d}{t} \cdot 90°$$

(4)

For shadowed side ($d \geq t$):

$$w' = w \cdot f_s$$
$$d' = \left(\frac{d-t}{180°-t} \cdot 90°\right) + 90°$$

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 5g):

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

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}, $s_{[\%]}$ is the slope (as a percentage), 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 5h).

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

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. This filter is only

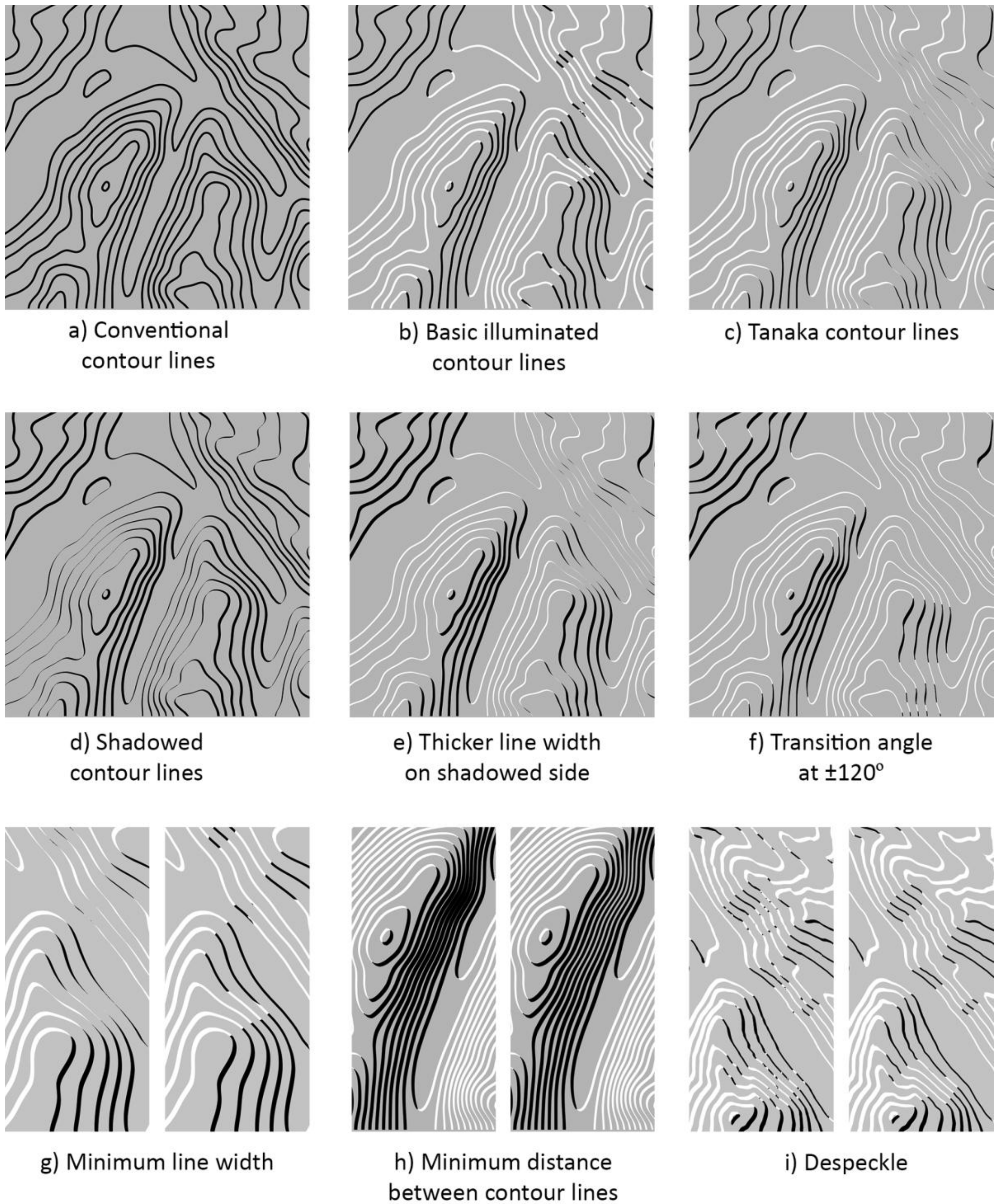

Figure 5. Steps in the computation of illuminated and shadowed contour lines.

applied to the computation of terrain aspect and does not affect the computation of slope, which is used in Equation 1. The amount of low-pass filtering is controlled by a parameter referred to as “despeckle” in the software (Figure 5i).

Additionally, 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).

The contour lines can be made to appear smoother 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.

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. Besides the illuminated and shadowed contour maps in the second question type, every fifth contour line was labeled, which was represented by an index contour in the conventional contour map. Maps were sized to 900 x 600 pixels and presented at screen resolution (Figure 6).

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. Shadowed contour lines have a minimum to maximum line width ratio of 1:4. The conventional contours have a standard contour line to index contour line width ratio of 1:3. The 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, U.S.A. The map locations used for the second question type represent twelve mountainous areas of equal extent around Ticino Valley, Switzerland. Participants were not informed about the location of the maps.

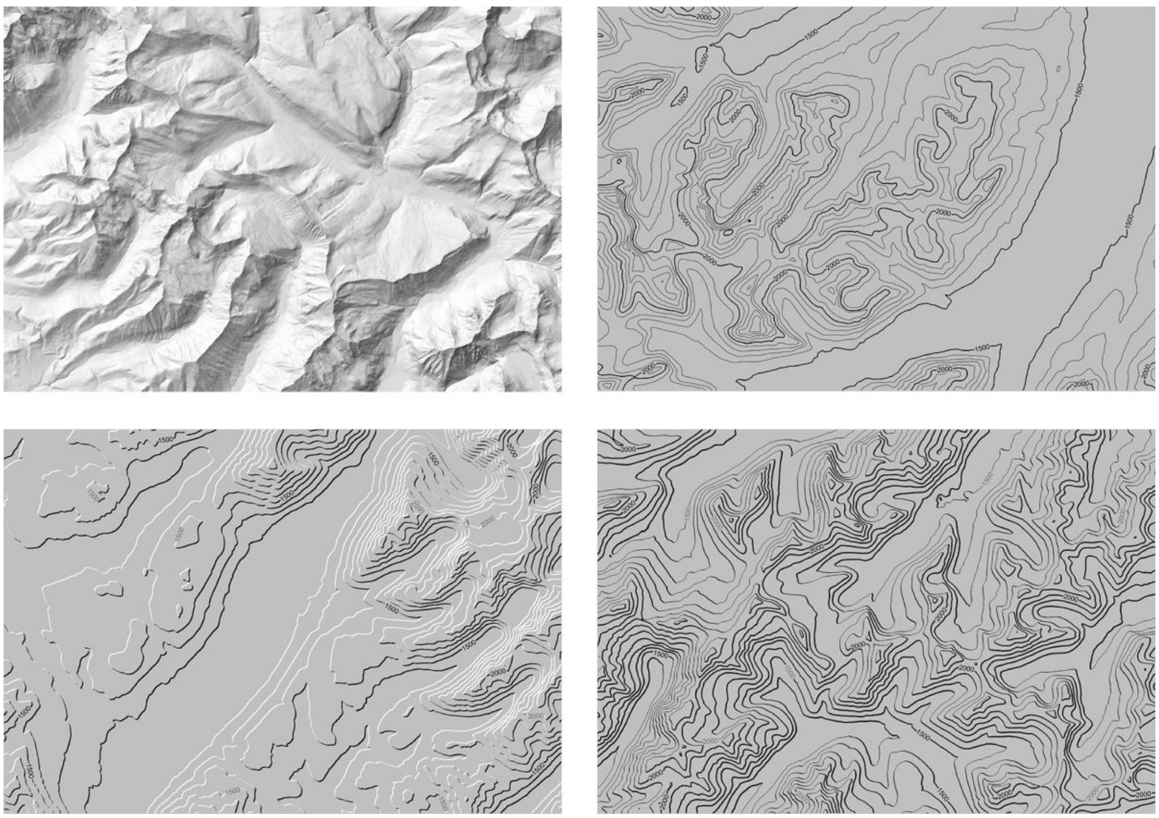

Figure 6. The four map types and locations used for the relative height questions in the user study. Top left: shaded relief; top right: conventional contour lines; bottom left: illuminated contour lines; bottom right: shadowed contour lines.

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 of each map type were summed and all possible combinations of pairs were tested.

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 was used to test all possible combinations of pairs (McCrum-Gardner 2008, Motulsky 2014). Because of the high number of results, 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 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, and the unanswered questions in the second question type were discarded. The average completion time for the study was 16 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 $\chi 2$-values being larger than the critical $\chi 2$-value (Table 2). There were no other significant differences between pairs of map types.

Table 1. Raw results for the relative height question (n = 3,970 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

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 7).

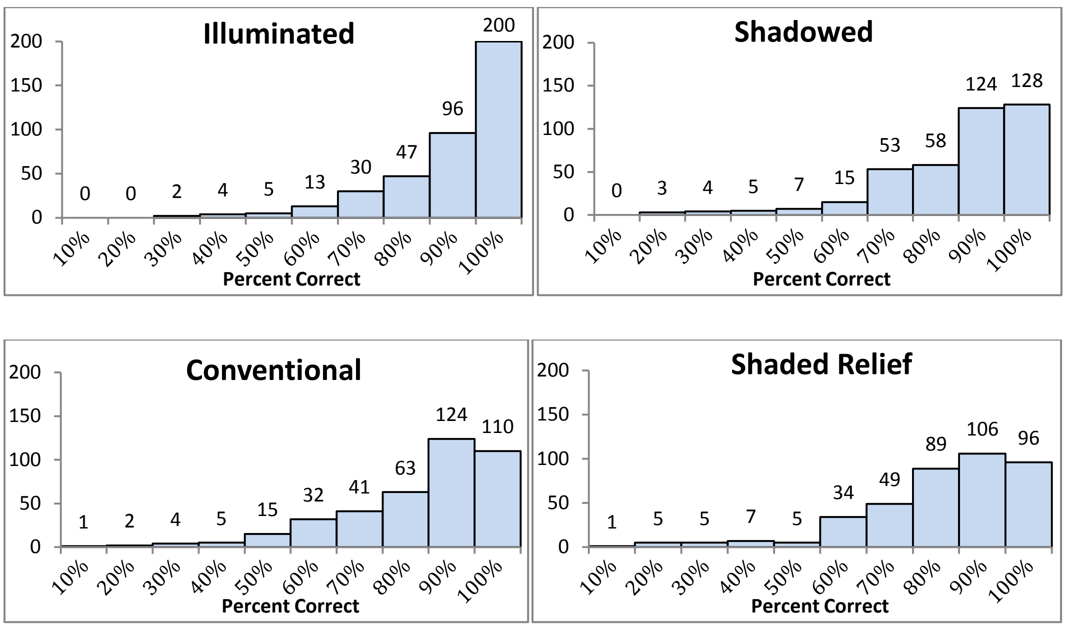

Figure 7. Histograms of the relative height question for illuminated, shadowed, and conventional contour lines, as well as shaded relief; percent correct per participant.

Table 2. McNemar's test results for the relative height question, χ2-crit = 3.8.

Map type pairs	χ2	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

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. Shaded relief and conventional contour lines had similarly poor results, with an accuracy of 81.9% correct answers for shaded relief and 83.4% correct answers for conventional contour lines.

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).

An effect size calculation shows a medium significance between illuminated contour lines and conventional contour lines. The pairwise test of effect size with shadowed contour lines and conventional contour lines shows 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 only provided a small advantage over conventional contour lines in terms of timing and accuracy.

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

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%.

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

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 and unlabeled shadowed contour lines as accurately as labeled conventional contour lines. Shaded relief maps scored significantly lower than all other map types.

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	0.01	no
Illuminated – conventional	0.741	no	X	X
Illuminated – relief	< 0.01	yes	0.38	med
Shadowed – conventional	< 0.01	yes	0.13	low
Shadowed – shaded relief	< 0.01	yes	0.27	low
Shaded relief – conventional	< 0.01	yes	0.39	med

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 contour lines as with labeled contour lines.

These timing results indicate that participants were able to accurately, and in the same amount of time, interpret height variation on the illuminated contour maps without labels as well as conventional contour maps with labels. 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. 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. 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 shaded relief maps (86.2%) (Figure 8). 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.

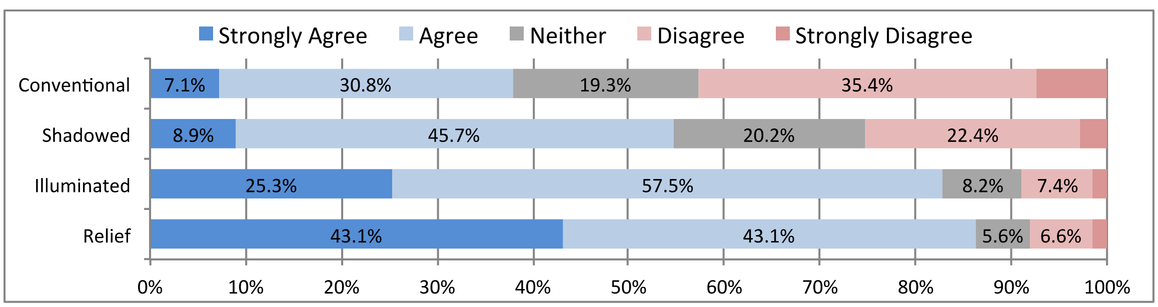

Figure 8. Participants' views on the statement that each map type shows variations in elevation well and produces an appearance of a three-dimensional space.

4.6. Demographics

Of the 397 participants, 327 were from the United States, 50 were from India, and 20 were from other countries. Results for each map type were about 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.

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

Study participants showed improved accuracy and map-reading speed for elevation comparison tasks 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 and shadowed contour maps with equal accuracy and speed as labeled conventional contour maps. In line with previous studies, shaded relief performed poorly compared to all contour map types for the identification of relative and maximum height on a map.

A contouring algorithm with new elements is 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. The contouring algorithm is integrated into Pyramid Shader, a free and open source software package.

Although the contour maps in this study were created using elevation data, the illuminated contour method can be applied to other statistical surfaces with equivalent results. Figure 9 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.

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. Detailed maps with many additional map elements may not be suitable for white and black contour lines. Future work is needed to test the effectiveness of different

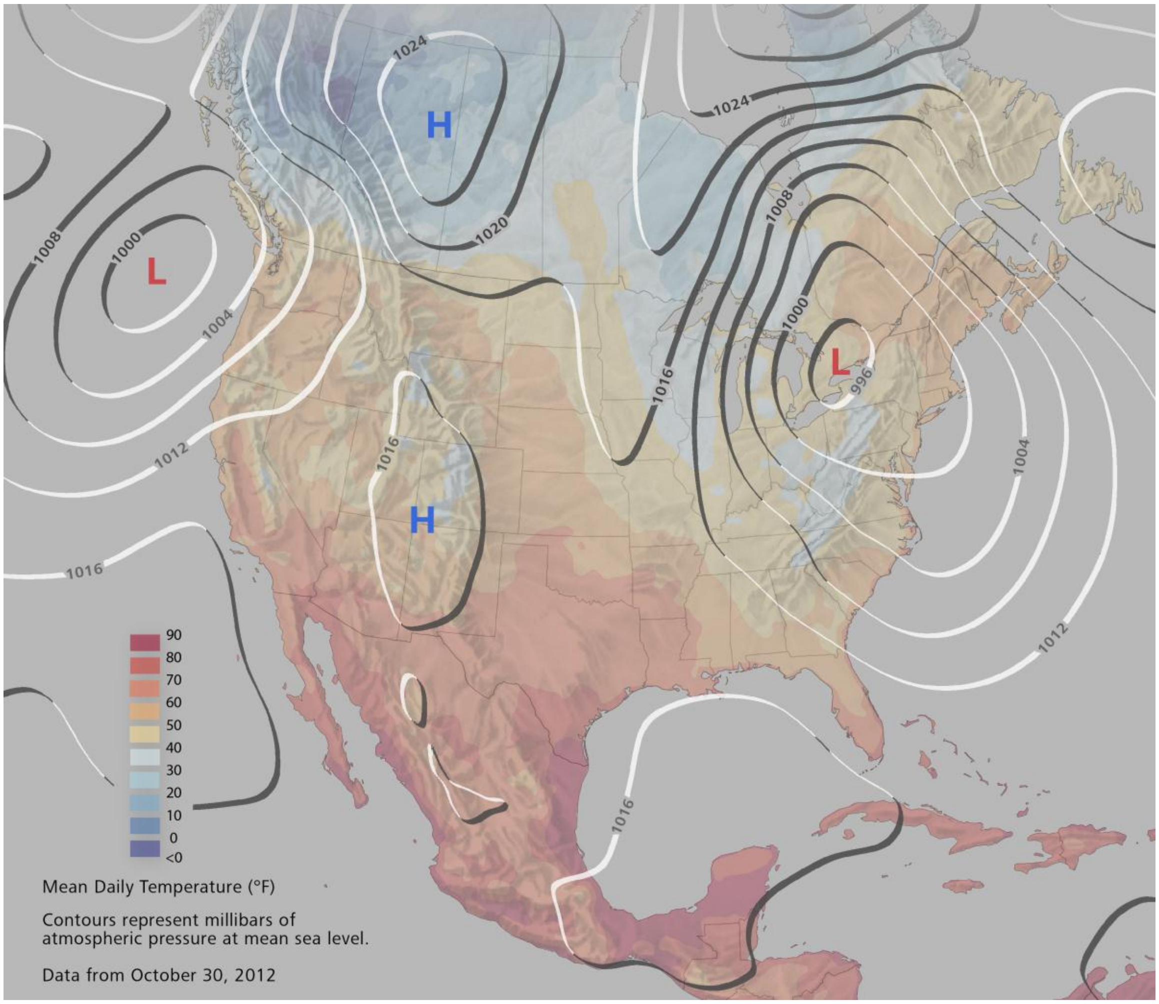

Figure 9. Multivariate weather map showing air pressure represented by illuminated contour lines and temperature represented by layer tints (Hurricane Sandy, October 30, 2012).

variations and more subtle implementations of the illuminated contour method. For example, bathymetric maps, which typically have fewer map elements than topographic maps, may benefit from the use of illuminated contour lines.

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