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Mitigating relief inversion illusion with multidirectional sky illumination model: A user study

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Abstract:

Relief presentation on maps has been developed in cartography for many centuries, yet it continues to receive attention in the digital era (e.g. Putto et al 2014). To represent elevation, relief is often illustrated as shading on shaded relief maps (SRM), typically using a single light source approximated by the Lambertian assumption (Kennelly & Stewart 2014). The recommended direction of the light source is from northwest (NW, azimuth 315°) (Imhof, 1965) or north-northwest (NNW, azimuth 337.5°) (Biland & Çöltekin 2017, Çöltekin & Biland 2019). When the light source is placed so that illumination comes from NW or NNW, the visualization should support comprehension of the SRM , specifically because it prevents a visual illusion which perceptually inverts the relief (Bernabé & Çöltekin 2014). As shown empirically by Biland & Çöltekin (2017), the strongest illusion appears for a light source with an azimuth of 225°. Relief inversion refers to users perceiving concave forms (e.g., a river valley on maps) as convex, and vice versa; concave shapes (such as mountain ridges on maps) are perceived by users as concave ones. This illusion, documented as early as 1786 by Rittenhouse (1786), is a result of the *overhead illumination bias*, meaning the human brain is used to processing images illuminated from above, which is the assumed direction of light, and if this is violated, previous implicit knowledge interferes with perceptual signal, and cognitive system can 'prefer' the previous knowledge, e.g., that the shadows are typically below the objects, and thus interpret the scene incorrectly.

While using a single light direction in SRMs is prone to the perceptual error described above, SRMs can also be rendered using multidirectional sky model illumination, such as the SkyLum model by Kennelly & Stewart (2014). SkyLum creates shading based on multiple light sources coming from a surrounding sky model - the sky "dome" to mimic the *Commission Internationale de l'Eclairage* (CIE) lighting models in the scene (Tranthan & Kennelly 2022, Kennelly & Stewart 2014). We hypothesize that multidirectional light sources may reduce or remove relief inversion illusion, a premise which has not yet been empirically tested. To address the gap stated above, we conducted a user study with 352 participants, Bachelor's degree students of geography at University of Warsaw. A between-subject study design was designed and conducted with the following shading types as independent variables: *Lambert vs. SkyLum*, and *azimuth: 225° vs. 337.5°*. For SkyLum shading we generated 250 light sources across the sky "dome" which included predominant azimuths to the southwest (225°) and the northwest (337.5°) using the open source tools of Tranthan & Kennelly (2022). *Response accuracy*, *response time*, *confidence*, and *perceived level of difficulty per task* were our dependent variables. Task types and landform orientations were applied as a within-subject independent variable. We selected ten areas of different landscape, ruggedness, and location from the collection of elevation models by Kennelly et al. (2021) to prepare the stimuli (Fig. 1).

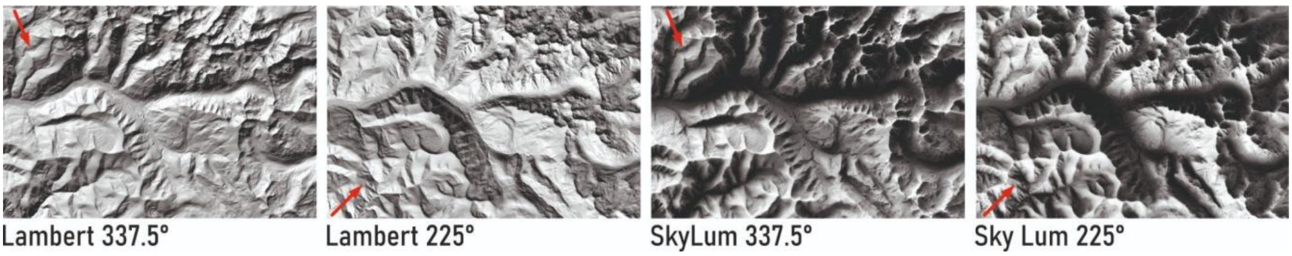

Figure 1. Example of stimuli: Gore Range (Colorado,USA) shaded relief maps with four tested settings of relief presentation. Red arrows indicating the light source direction were not shown to participants.

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The results show the effect of shading type and azimuth on the accuracy of responses, with significantly worse scores for participants evaluating shaded relief maps with Lambert 225°. Response time, as well as the subjective metrics of confidence and perceived difficulty of a task, were not affected by the tested shading settings. This indicates that participants did not make an additional effort when giving less accurate answers while experiencing relief inversion illusion on Lambert 225°, thus the illusion was probably strong. Moreover, landform orientation affected response accuracy for both types of tested shadings (Lambert and SkyLum), but only with azimuth of 225°.

Our results show that a multidirectional sky illumination model helps in mitigating the relief inversion illusion when creating shaded relief maps with the predominant lighting direction from the southwest, significantly improving the accuracy in landform and elevation change recognition.

References

Bernabé-Poveda M-A., Çöltekin A., 2015. “Prevalence of the terrain reversal effect in satellite imagery”. *International Journal of Digital Earth* 8(8): 640-655.

Biland J., Çöltekin A., 2017. “An empirical assessment of the impact of the light direction on the relief inversion effect in shaded relief maps: NNW is better than NW”. *Cartography and Geographic Information Science,* 44(4): 358-372.

Çöltekin A., Biland, J., 2019. “Comparing the Terrain Reversal Effect in Satellite Images and in Shaded Relief Maps: An Examination of the Effects of Color and Texture on 3D Shape Perception from Shading”. *International Journal of Digital Earth* 12(4): 442-459

Imhof E. 1967. “Shading and Shadows.” In *Cartographic Relief Representation,* H. J. Steward (ed.), Vol. 2007, 159–212. Berlin: Walter de Gruyter GmbH & Co KG.

Kennelly P., Stewart J., 2006. “A uniform sky model to enhance shading of terrain and urban elevation models”. *Cartography and Geographic Information Science* 33(1): 21–36.

Kennelly P., Stewart, J., 2014. “General sky models for illuminating terrains”. *International Journal of Geographic Information Science* 28(2): 383-406.

Kennelly P.J., Patterson T., Jenny B., Huffman D.p., Marston B.e E., Bell S., Tait A.M. 2021. “Elevation models for reproducible evaluation of terrain representation”. *Cartography and Geographic Information Science,* 48:1, 63-77

Putto K., Kettunen P., Torniainen J., Krause C. M., & Tiina Sarjakoski, L., 2014. Effects of Cartographic Elevation Visualizations and Map-reading Tasks on Eye Movements. *The Cartographic Journal,* 51(3): 225–236

Rittenhouse D. 1786. “Explanation of an Optical Deception.” *Transactions of the American Philosophical Society* 2: 37.

Trantham G., Kennelly P., 2022. “Terrain representation using orientation”, *Cartography and Geographic Information Science* 49(6): 479-491.

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