Terrain maps are often composed of shaded relief along with other raster layers which we call thematic terrain layers to create aesthetically pleasing and clear maps of physical geography. Despite that the interplay of layers is of primary concern to a cartographer, much of the research on terrain mapping has focused on studying terrain layers individually. This research aimed to fill this gap by evaluating the effect of combining shaded relief with thematic terrain layers and assessing ratings of beauty, realism, and landform clarity in an exploratory online user study. Specifically, we tested the combination of: manual, multidirectional, and ray-traced shaded relief with three thematic terrain layers: hypsometric tinting, land cover, and orthoimagery. There are five main findings from this exploratory study: (1) there was a direct correlation between beauty and realism scores, (2) the manual relief we tested was consistently rated lowest for beauty, realism, and landform clarity, and orthoimagery was rated the highest for beauty and realism, (3) shaded relief was more influential than thematic terrain layers on landform clarity ratings, (4) participant’s geographic familiarity had a significant impact in four specific instances of the user study, and (5) neither shaded relief or thematic terrain layers were the sole contributors to map reader perceptions of beauty, realism, or landform clarity. We conclude by identifying limitations in our stimuli design and presenting ideas for future research studies on terrain design.

KEYWORDS: aesthetics; terrain mapping; shaded relief; landform clarity; perception, beauty; realism; cartography; map design; hillshade

INTRODUCTION

Shaded relief, relief shading, and hillshading are terms often used interchangeably to refer to the cartographic technique of creating intuitive and realistic representations of topographic features on maps by mimicking the shadows cast by a light source. Shaded relief was initially created manually with an airbrush, pencil, or similar methods. However, modern digital processes have simplified the creation of beautiful, realistic, and clear relief for maps. We commonly access these tools in geographic information systems (GIS), but novel methods are increasing in popularity, some of which use 3D rendering software (Huffman 2017). Such tools allow cartographers to create shaded relief that more closely mimics the expressiveness and beauty of early manual shaded relief, but is more easily reproducible and time efficient.

The cartographer’s chosen shaded relief method is not necessarily the sole contributor to a successful terrain map. Shaded relief is frequently combined with other raster layers, such as imagery or land cover, to create maps that offer the reader a clearer idea of the complexity of the landscape. The fact that these combinations are so popular suggests that an interaction between shaded relief and thematic terrain layers is often necessary to enhance the perceived beauty, realism, and clarity of the representation. Empirical research on relief shading has increased over the past decade, providing insight into new digital techniques to represent the topographic relief on maps (Jenny 2021; Jenny et al. 2020; Kennelly and Stewart 2014; Marston and Jenny 2015), user perception of illumination angles (Biland and Çöltekin 2017), and the perceived effectiveness of relief shading techniques (Farmakis-Serebryakova and Hurni 2020). However, few studies have investigated shaded relief combined with other thematic terrain layers (e.g. Çöltekin and Biland 2019; Huffman and Patterson 2013; Raposo and Brewer 2014). In these examples,
authors focused on one type of shaded relief and one type of thematic terrain layer, but to our knowledge, none of these studies specifically measured perceptions across combinations of different shaded relief designs and thematic terrain layers.

In this study, our goal was to better understand how the combination of shaded relief and thematic terrain layers affect map readers’ perceptions of beauty, realism, and landform clarity. After examining two volumes of the North American Cartographic Information Society (NACIS) Atlas of Design (Steingisser, Rose, and Tierney 2018; Marston et al. 2020), along with award-winning maps from the NACIS Conference, we identified three shaded relief techniques that were commonly used: (1) manual shaded relief, (2) multidirectional shaded relief, and (3) ray-traced relief. In addition, cartographers often paired these types of shaded relief with other layers to portray the landscape more realistically. Across the selection of maps we viewed, many included (1) hypsometric tinting, (2) land cover, or (3) orthoimagery. After reviewing these maps, our study was guided by the following research question:

**How do manual and analytical shaded relief techniques influence reader perceptions of beauty, realism, and landform clarity in terrain maps that incorporate hypsometric tinting, land cover, and orthoimagery?**

Cartography is as much an art as it is a science (Cosgrove 2005). Thus, it makes sense to understand not only the effects of combining different layers to create terrain maps, but also how those combinations affect the perceived beauty, realism, and the clarity of landforms in a two-dimensional map.

The rest of the paper is organized as follows: in the next section we describe shaded relief and thematic terrain layers, then we describe the importance of aesthetics in cartography. We follow with a description of our methods for an exploratory online user study. In the fourth section we illustrate the results of our exploratory study and follow with a discussion of those results. In the final section of the paper, we conclude with an overview of our findings, some limitations, and future research ideas.

**BACKGROUND**

**SHADED RELIEF**

Shaded relief began as a hand-drawn art form that gave depth to a two-dimensional view from above by accurately representing landforms using localized light sources (Marston and Jenny 2015; Imhof 1982; Brassel 1974; Collier, Forrest, and Pearson 2003). Manual relief has its own individual styles, determined by the cartographer who designed the map. This means that these maps are difficult to reproduce since any two cartographers are likely to draw very different representations of the same location due to their personal style, skill level, and interpretation of the landscape. Manual techniques also allow a cartographer to adjust their representation to meet the needs of the particular landscape being shown. However, creating these maps manually is extremely time-intensive, though generalization is a common way to reduce the time burden (Patterson 2018). Recently, there has been a reinvigorated interest in exploring manual techniques amongst contemporary practicing cartographers (e.g., Bell 2018), while cartographic researchers have also attempted to replicate the aesthetic quality of manual relief through algorithmic processes, allowing the style to be more available to digital mapmakers (Jenny et al. 2020).

With the onset of computers, digital, analytic methods took over manually-created shaded relief due to the speed and consistency with which the cartographer could now create these types of terrain layers. Basic analytical relief shading can be created quickly in a GIS from a digital elevation model (DEM). Since this standard shaded relief algorithm uses a single light source, all landforms are treated equally, which sometimes results in (1) less explicit landscape depictions with a lack of structure in larger landforms (Marston and Jenny 2015), and (2) a lack of clarity for minor landforms, especially those within the shadowed slopes of larger landforms (Zakšek, Oštir, and Kokalj 2011). Adjusting the light angle to better capture most landforms in a relief map is one solution to this limitation (Biland and Çöltekin 2017). Multidirectional
shaded relief also provides a solution by casting multiple light sources from different sun angle directions (Loissios, Tzelepis, and Nakos 2007; Mark 1992; Tzelepis et al. 2020; Veronesi and Hurni 2014) and is now more easily accomplished in GIS.

Of growing interest to practicing cartographers, however, is the use of 3D rendering software to create shaded relief maps, specifically ray-tracing methods. Ray-tracing is a well-known computer graphics technique for 3D modeling and can simulate natural light to create photo-realistic digital images (Glassner 1989; Rademacher 1997). Similar to GIS methods for rendering relief, ray-tracing produces a 2D greyscale image given a light source direction. The major difference from typical GIS methods is that ray-tracing can render more complex optical effects and surface textures, which makes it a unique tool for depicting topographic relief. While an analytical hillshade algorithm determines a pixel’s shading based solely on its orientation toward a light source, without accounting for any of the rest of the landscape, ray-tracing can model the light as it reflects, refracts, scatters, and diffuses off the adjacent surfaces (Huffman 2014; Morgan-Wall 2018; Stevens 2014). A handful of cartographers have openly shared tools, tutorials, and processes for generating relief using a 3D modeling program called Blender (blender.org), which utilizes ray-tracing algorithms (Huffman 2017; Powell 2016; Underwood 2019; Larson 2019; Atwood 2020). These materials have made this method for generating shaded relief more accessible and reproducible.

**THEMATIC TERRAIN LAYERS**

While shaded relief is often the key element in representing the physical landscape in terrain maps, it is just one layer. To create a more complete image of the terrain, shaded relief is typically paired with additional layers to provide context to the underlying landscape (Imhof 1982; Imus and Loftin 2012). Some of these layers can be derived from the elevation surface and augment the visualization of elevation change; Imhof (1982) refers to these layers as “abstractions,” and they include hypsometric tinting, hachuring, and contour lines. In addition, layers such as land cover and orthoimagery can represent variation in vegetation and surface cover to add context and texture to the map.

In this exploratory research, we focus specifically on three layers which are commonly used in terrain mapping: hypsometric tinting, land cover, and orthoimagery (Figure 1). Hypsometric tinting is a method of representing elevation values using a continuous or classed single hue, multi-hue, or spectral color scheme (Figure 1, A). This, combined with shaded relief, reinforces elevation heights through color cues. However, using an evenly stretched scheme on world maps can cause a loss of lowland and highland detail, which can be remedied by creating locally enhanced hypsometric tinting (Huffman and Patterson 2013). In addition, the colors used may mislead a map reader if they do not directly represent the underlying geography. Many authors suggest that the colors in elevation tinting should reflect hues one might see in the natural landscape (Imhof

![Figure 1. (A) Hypsometric tint colorizing high elevations with a pale yellow color and lower elevations in darker pale green; (B) data from the National Land Cover Database with naturalistic colors applied to the land cover classes; (C) orthographic imagery (from Google) giving readers a realistic sense of the terrain.](image-url)
1982; Patton and Crawford, 1977; Patterson and Jenny 2011). Land cover (Figure 1, B), in comparison, is a separate dataset which is often paired with shaded relief to create a naturalistic aesthetic (Patterson 2002). Land cover is typically stored as a raster dataset, in which each cell is assigned a singular land cover type (e.g., forest). Finally, orthographic imagery (Figure 1, C), such as geometrically corrected aerial photos or satellite images, can allow for instant recognition of place through the landforms, and the texture of the underlying topography (Peterson 2012; 2020). Supporting this claim, Hoarau and Christophe (2017) found that orthoimagery in maps adds realism and context, while other research has contradicted this by showing negative effects on map readers. For example, Çöltekin and Biland 2019 found that, when paired with shaded relief, orthoimagery can negatively affect landform perception.

AESTHETICS

The very nature of relief representation is rooted in artistic qualities and requires that careful thought be given to the aesthetic characteristics of a map (Imhof 1982). Cartographers frequently debate aesthetics, because of cartography's close ties to art and visual representation. As Kent et al. (2012) state “opinions are strong and varied [regarding aesthetics] and there are no universal rules, even though when we say a map is ‘beautiful’ we believe others ought to agree with us.” Regardless of the data conveyed and message being shared, the map must appeal in its representation (Field and Demaj 2012). While learning a set of rules and conventions for representing map features is conceivable, a cartographer’s goal with a map is to not only be informationally effective but also aesthetically pleasing (Dent 2008).

METHODS

To answer the research question, we designed a within-subject user study to examine: (1) beauty, (2) realism, and (3) landform clarity across a set of maps with variations in shaded relief and thematic terrain layers.

PARTICIPANTS

We solicited 105 participants for the study from the recruitment site Prolific. Participants were able to participate if they were using a desktop computer and their Prolific profile indicated they were 18 years of age or older, a US resident, and fluent in English. Each participant was paid $4.97 USD through Prolific for approximately 15 minutes of their time after they completed the user study, and we approved their answers.

STIMULI

The stimuli for the user study consisted of nine different terrain maps of Crater Lake, Oregon, in the United States.
The maps were made up of a combination of three shaded relief layer designs and three thematic terrain layer designs (Figure 2).

The three relief layers we used were: (1) a manual shaded relief created by Bill von Allmen of the US National Park Service in 1988 and later edited by Tom Patterson, (2) a multidirectional shaded relief, and (3) a ray-traced shaded relief. We downloaded the manual relief map from the Shaded Relief Archive (shadedreliefarchive.com/Crater-Lake.html). The analytical relief layers (multidirectional and ray-traced) were derived from a 3.33-meter resolution DEM from a set of sample elevation models provided by Kennelly et al. (2021), and the bathymetry was derived from a 1-meter ASCII XYZ grid re-sampled to 3.33 meters (pubs.usgs.gov/dds/dds-72/site/gridfaq.htm#getacopy). The multidirectional shaded relief was created in QGIS (version 3.16.3) using the GDAL hillshade tool. The following parameters were set for the hillshade tool: vertical exaggeration (Z factor) was set to 3.0, the azimuth was set to 337.5 as suggested by Biland and Çöltekin (2017), the altitude was set to 45.0 degrees, with the multidirectional shading option. Our ray-traced relief map was created in Blender (version 2.82a). Using Blender for relief modeling requires the DEM to be converted to a 16-bit unsigned integer, which we did using a GDAL Warp command (Larson 2019). The parameters we used to create the ray-traced relief in Blender mimicked what is detailed in Huffman’s tutorial (2017). The only deviating parameter we used the surface displacement method, which we set to “Displacement and Bump.” This option combines both the displacement option, allowing for larger amounts of displacement in the 3D model, and the bump mapping option, which preserves finer details and textures in the rendering. Combining the two methods can provide a good balance and reduce memory usage (Blender Documentation Team 2021).

The three thematic terrain layers we used were: (1) hypsometric tint, (2) land cover, and (3) orthographic imagery. The hypsometric tint layer was created from the same DEMs as the analytical shaded relief layers and used two separate color schemes, one for land surface elevations, using colors designed to mimic the vegetation and land cover of the region as suggested by Patterson and Jenny (2011), and a second color scheme for bathymetric depths. The land cover layer used raster data collected from the National Land Cover Database (NLCD), reclassified into three land cover types: (1) tree cover, (2) shrub/grass, and (3) water. Finally, the orthographic image layer was derived from Google Maps. To avoid over saturation and opposing shadows, we used the content-aware fill tool in Photoshop on areas of the orthoimage that appeared to be shaded so they did not conflict with the shaded relief’s shadows.

There were two limitations of our stimuli design that we acknowledge could have had a confounding effect on the eventual results. First, von Allmen’s manual relief depicted more generalized land and bathymetric relief and thus had less detail in the landforms depicted, compared to the multidirectional and ray-traced relief models. Second, we did not control for contrast, lightness, or saturation across the nine maps. We discuss the implications of these limitations more in the conclusion.

**USER STUDY PROCEDURE**

Participants found the study through the Prolific recruitment site. Once they clicked on the study, they were redirected to a Qualtrics site to take part in the user study. Participants were first asked to enter their Prolific ID and read through the consent form. Participants then continued to the four sections of the study: (1) a pre-test
questionnaire, (2) a tutorial, (3) the main user study, and (4) a final feedback question. The pre-test questionnaire consisted of six questions: two demographics questions on gender and education level, a question about their knowledge of cartography and map design, and three questions about their familiarity with the geographic focus of the study, Crater Lake, asking whether they had (1) heard of, (2) seen pictures or maps of, (3) or visited the area. Following the pre-test, participants navigated through a tutorial where they were introduced to the five rating tasks they would complete during the main user study. The tutorial used only three map designs and depicted a different geographic area, Churfürsten, Switzerland (Figure 3). This section introduced the term “terrain map,” the purpose of relief shading in maps, and asked participants to rate the sample maps for their “beauty,” “realism,” and “landform clarity” (Figure 4).

In this study, you will be answering questions about terrain maps. These maps use shading techniques to represent topography as if the map were three-dimensional. Terrain maps are effective because they accurately represent the earth’s surface.

Terrain maps also provide a pleasing aesthetic appeal and are often known for being both beautiful and realistic.

The example below shows a terrain map without any labels. You are being asked to comment on the overall aesthetic appeal of this map.

Figure 3. Three variations of Churfürsten, Switzerland were used to introduce participants to the rating tasks they would be completing later in the study. The manual shaded relief was created by Eduard Imhof in 1947 (shadedreliefarchive.com/NortheastSwitzerland.html).

Figure 4. The tutorial section introduced the beauty, realism (left), and landform clarity (right) tasks to prime participants for the main portion of the user study.
Following the tutorial, participants started the main user study. In the main user study, the participants answered the same five questions they were introduced to in the tutorial, but for nine map designs, for a total of 45 questions. The five rating tasks per map design were divided across two web pages in Qualtrics. The first page included one of the nine stimuli maps and asked participants to rate its beauty and realism (Figure 5, left). The second page showed the same map with numbered annotation on the three landforms (Wizard Island, Mount Scott, and Grouse Hill) and asked participants to rate the clarity of those landform (Figure 5, right). We selected these three

![Figure 5](image-url)

*Figure 5.* Example from the study asking a user to rate the beauty, realism (left), and landform clarity (right) of the Crater Lake map design blending hypsometric tint and ray-traced relief.
landforms because they were similar in size and were located proximally to the main landform feature in the map (Crater Lake). Since the study was within-subject, all participants saw all nine of the map designs. These were presented in random order for each participant to limit the possibility of a learning effect. Once participants finished the 45 rating tasks in the main user study, they were shown a final feedback question. The final feedback question of the user study asked participants to “Please provide any comments or feedback on your experience while taking part in this study,” to gain qualitative insights on the stimuli design, user experience, and study design. Two attention-check questions were presented to participants during the study to ensure they were actively engaging in the survey. Once they finished all the questions, they were redirected back to Prolific and compensated for their time once we approved their answers.

ANALYSIS

First, we tested the data for normality using a Shapiro-Wilk test, and then we tested for equality of variance using a Levene’s test. The results indicated that most of our data were not normally distributed and failed to demonstrate homogeneity of variance. Given this, non-parametric tests would be best suited for our data. However, there is some debate over to what degree the violation of these two assumptions affects statistical results (Scariano and Davenport 1987; Lix, Keselman, and Keselman 1996), and so we felt comfortable performing a parametric test: a two-way ANOVA with a Tukey HSD post-hoc test.

This ANOVA test was used to assess whether the choice of shaded relief and thematic terrain layers had a significant effect on beauty, realism, and landform clarity ratings. We chose a two-way ANOVA because in addition to independently testing the effect that shaded relief and thematic terrain layers had on rating scores, it also determines if there is a significant interaction effect between the two layers. This ability makes the two-way ANOVA a more robust and valuable analysis for studies with two categorical independent variables (Norušis 2012). Essentially, an interaction occurs when “the effect of one independent variable is not the same for all levels of the other independent variable” (Rahman 2019). However, since most of the samples failed the assumptions for a parametric analysis, we also ran a Welsh and Brown-Forsythe test to validate the ANOVA results. We then ran a Spearman’s rank-order correlation to test the relationship between beauty and realism rating scores.

RESULTS

Of the initial 105 respondents, we removed ten responses because of incomplete answers, failed attention checks, or an indication that they had expert knowledge of cartographic design, leaving 95 total responses for analysis. Forty-eight of the participants indicated they identified as female, 46 identified as male, and one identified as non-binary. Most of our participants either had some college education (20%) or a 4-year degree (38%). When indicating their familiarity with Crater Lake, 64% had heard of it, 42% had seen photos or maps, and 11% had once visited Crater Lake. Since our project was an exploratory examination of our research question, we did not formulate a hypothesis for the results. However, we did run a series of statistical analyses that would help us better understand the relationships between perceived beauty, realism, and landform clarity among our user study population.

BEAUTY AND REALISM RESULTS

Both beauty and realism had similar results from the two-way ANOVA. The beauty rating task showed a significant main effect for both shaded relief (F(2,4) = 13.495, p < 0.001), and thematic layer (F(2,4) = 94.520, p < 0.001), but we found no significant interaction between the two (F(2,4) = 1.799, p = 0.115) for the beauty rating scores. The thematic terrain layers had a higher effect size (η² = 0.18) on beauty rating scores than shaded relief (η² = 0.03). Similarly, the realism rating task showed a significant main
That's a Relief

– Douglass & Fish  | 9

The effect for both shaded relief ($F(2,4) = 16.46, p < 0.001$), and thematic layer ($F(2,4) = 132.996, p < 0.001$), but no significant interaction between the two ($F(2,4) = 2.202, p = 0.067$) on realism rating scores. Thematic terrain layers also had a higher effect size ($\eta^2 = 0.24$) on realism rating scores than shaded relief ($\eta^2 = 0.04$).

The Spearman’s rank-order correlation showed a statistically significant relationship ($rs(8) = 0.653, p < 0.001$) and indicated there was a positive correlation between beauty and realism rating scores. Figure 6 shows the estimated marginal means plotted for beauty and realism. The estimated marginal means are the mean beauty and realism scores for each thematic terrain layer averaged across the three shaded relief techniques.

The shaded relief Tukey HSD post-hoc test results were similar between the beauty and realism tasks. Results of the post-hoc revealed that beauty and realism scores for von Allmen’s manual shaded relief were statistically significantly lower than both the ray-traced relief ($p = 0.001$ for beauty; $p < 0.001$ for realism) and multidirectional shaded relief ($p < 0.001$), and there was no significant difference between multidirectional shaded relief and ray-traced relief (Figure 7, A).

The Tukey HSD post-hoc test results for the thematic terrain layers differed slightly between the beauty and realism tasks. The tests revealed that beauty scores for orthoimagery were statistically significantly higher than both

Figure 6. Estimated marginal means of beauty and realism scores from the two-way ANOVA. This graph shows the weighted means of beauty and realism scores for each thematic terrain layer averaged across the three shaded relief techniques. Greater distance between lines on the y-axis indicates a greater difference in rating scores for the combination of relief and thematic terrain layer.

Figure 7. Pairwise comparison of beauty and realism results from the Tukey HSD post-hoc test.
hypsometric tinting ($p < 0.001$) and land cover ($p < 0.001$); but there was no significant difference between hypsometric tinting and land cover. The post-hoc test for realism rating scores showed that all thematic terrain layers differed significantly from one another ($p < 0.001$), confirming that orthoimagery was perceived as the most realistic and hypsometric tinting as the least realistic (Figure 7, B).

**LANDFORM CLARITY RESULTS**

Across the three landforms (Wizard Island, Mount Scott, and Grouse Hill), results of the two-way ANOVA were not as consistent as beauty and realism scores. For Wizard Island, the results of the two-way ANOVA showed a significant main effect for both shaded relief ($F(2,4) = 25.28$, $p < 0.001$), and thematic layer ($F(2,4) = 17.187$, $p < 0.001$), and a significant interaction between the two ($F(2,4) = 3.196$, $p = 0.013$) on clarity rating scores. Mount Scott also showed a significant main effect for both shaded relief ($F(2,4) = 21.76$, $p < 0.001$), and thematic layer ($F(2,4) = 10.86$, $p < 0.001$), and a significant interaction effect ($F(2,4) = 2.798$, $p = 0.025$). However, Grouse Hill only showed a significant main effect for shaded relief ($F(2,4) = 44.16$, $p < 0.001$) and a significant interaction effect ($F(2,4) = 2.798$, $p = 0.014$), but thematic terrain layers were not significant ($F(2,4) = 0.641$, $p = 0.527$). One similarity across the three landforms was that shaded relief had a higher effect size (Wizard Island: $\eta^2 = 0.056$; Mount Scott: $\eta^2 = 0.049$; Grouse Hill: $\eta^2 = 0.095$) on landform clarity scores than thematic terrain layers (Wizard Island: $\eta^2 = 0.039$; Mount Scott: $\eta^2 = 0.025$; Grouse Hill: $\eta^2 = 0.002$). Figure 8 shows the estimated marginal means of landform clarity scores plotted for each landform, which are the mean landform clarity scores for the shaded relief technique averaged across each thematic terrain layer.

The Tukey HSD post-hoc tests for shaded relief were similar for Wizard Island and Grouse Hill, but Mount Scott
had differences (Figure 9, A). The results showed all shaded relief methods were significantly different from one another \( (p < 0.05) \) for Wizard Island and Grouse Hill. However, for Mount Scott, von Allman's manual relief differed significantly from the other two shaded relief designs \( (p < 0.001) \); but multidirectional shaded relief and ray-traced relief were not significantly different from one another \( (p = 0.213) \).

For thematic terrain layers, the HSD post-hoc tests showed similar results between Wizard Island and Mount Scott, but not for Grouse Hill (Figure 9, B). Wizard Island and Mount Scott showed there was a significant difference between hypsometric tint and land cover (Wizard Island: \( p = 0.001 \); Mount Scott: \( p < 0.001 \)); hypsometric tint and orthoimagery were significantly different \( (p < 0.001) \); but orthoimagery and land cover were not significantly different (Wizard Island: \( p = 0.051 \); Mount Scott: \( p = 0.931 \)). Results for Grouse Hill indicated that thematic terrain layers were not a significant main effect, thus there was no significant difference between hypsometric tint, land cover, and orthoimagery.

**Figure 9.** Pairwise comparison of landform clarity for Wizard Island, Mount Scott, and Grouse Hill from the Tukey HSD post-hoc test.
GEOGRAPHIC FAMILIARITY RESULTS

Geographic familiarity had no significant effect on participant’s combined mean rating scores for beauty, realism, and landform clarity (Table 1). However, geographic familiarity had a statistically significant impact on four specific map designs between groups for each familiarity question (Table 2). Even though more participants had heard of Crater Lake (N = 61, M = 42.98), those who had not heard of Crater Lake (N = 32, M = 57) had higher clarity ratings for Wizard Island when looking at the map design with multidirectional shaded relief and hypsometric tinting (U = 1343, p = 0.009). Participants who had seen photos or maps of Crater Lake (N = 40, M = 56.44) showed higher...
realism ratings for the map using multidirectional shaded relief and hypsometric tinting (U = 762.5, p = 0.008) then those who had not seen maps or photos of Crater Lake (N = 55, M = 41.86). Those same participants who had seen photos or maps of Crater Lake (N = 40, M = 64.90) also showed higher clarity ratings for Wizard Island when looking at the map design using multidirectional shaded

DISCUSSION

BEAUTY AND REALISM RATING TASKS

Overall, there were a wide variety of responses to the beauty and realism rating tasks, and the ratings depended on the shaded relief and thematic terrain layers used. The ratings were more influenced by the thematic terrain layers than shaded relief designs in our stimuli, although they were both significant. And while both shaded relief and thematic terrain layers were significant, the scores were not dependent on the combination of thematic terrain and shaded relief, rather the two variables had unique outcomes on user perceptions. Finally, the outcomes from both tasks showed there to be a correlation between perceived beauty and realism.

The effect of shaded relief on the beauty and realism ratings showed that participants consistently rated von Allmen’s manual relief as the least beautiful and realistic of the three shaded relief methods. To some, this may be a surprising finding, because the cartographic community time and again has pointed to manual relief as the most artistic and realistic technique for representing terrain (Imhof 1982; Brassel 1974; Collier, Forrest, and Pearson 2003; Marston and Jenny 2015). However, this result confirmed our expectations, since manual relief inherently is tied to the cartographer’s individual interpretation of the landscape through generalization (Patterson 2018). Our ray-traced relief and multidirectional shaded relief were both rated highly for perceived beauty and realism; however, even though multidirectional relief had a higher mean score compared to the ray-traced relief, the ratings were not significantly different between the two, so we cannot conclude if one was truly perceived as more beautiful or realistic.

For the thematic terrain layers, map readers found orthographic imagery to be the most beautiful and realistic. Orthographic imagery often adds more visual complexity than other thematic terrain layers, and tends to feature darker colors, making it a challenging layer to pair with overlaying vector data (Hoarau, Christophe, and Mustière 2013). It was surprising to see that orthoimagery was rated as the most beautiful, but this finding might suggest that visually complex images can be deemed aesthetically preferable. It was, however, not surprising that orthoimagery was the highest rated for the realism task, given the literature (Hoarau and Christophe 2017; Peterson 2012). This confirms Peterson’s (2012) notion that incorporating satellite imagery into maps, such as with Google Maps, Google Earth, and other online navigation maps, provides context and an aesthetic that is more relatable to average map users. Further, common web map applications rarely use hypsometric tinting and land cover, which could have contributed to orthoimagery being rated higher in the beauty and realism rating tasks, since average map readers are more (and increasingly) familiar with imagery. Land cover and hypsometric tinting were both rated lower for perceived beauty and realism; however, for beauty ratings, the two thematic terrain layers were not significantly different, but for realism ratings, the results indicated that hypsometric tinting was perceived as the least realistic. This finding may have some merit, since hypsometric tinting is an abstraction of reality and, depending on the design, it is not always a realistic visualization of how the landscape looks. Depending on the location and the colors used in the representation, it has the potential to convey inaccurate information about vegetation, rainfall, or temperature (Patton and Crawford 1977). It was clear from these results that the combination of von Allmen’s manual shaded relief and hypsometric tinting do not elicit a strong sense of realism, especially when compared to other depictions that use orthoimagery.

Our research found, regarding aesthetics, that more realistic images (maps with orthoimagery) were ranked higher
than abstract images (maps with land cover or hypsometric tinting). This is interesting because researchers who have studied the effects of naïve realism posit that photorealist-
tic representations are strongly desired by participants, de-
spite exhibiting lower performance scores in map interpre-
tation as compared to abstract representations (Hegarty et al. 2009; Smallman and St. John 2005). Since our research did not have a series of map reading
tasks, we cannot gauge if map interpretation is also negatively
affected by more realistic rep-
resentations. However, partic-
ipants were clearly more drawn
to orthoimagery for its aesthetic
appeal. More research should
be done to investigate the dif-
ference in map preference and
performance as it is related to
thematic terrain layers.

One of the most surprising find-
ings was the direct correlation
between beauty and realism scores. Cartographers have al-
luded to a connection between

Figure 10. Heatmap showing the frequency of correlated beauty and realism responses for the entire user study. Participants
frequently rated maps with the same Likert value for both beauty and realism. The graph shows a positive correlation between the
two rating variables.

landform clarity rating tasks

The results of the user study showed that landform clarity ratings differed from beauty and realism ratings in certain ways but had some similarities as well. Much like the outcomes from the beauty and realism ratings, von Allmen’s manual relief was rated lowest. Unlike the beauty and realism ratings, the landform clarity ratings showed that shaded relief was more influential on participant perceptions of landform clarity than thematic terrain layers. There was

Figure 11. Comparison of estimated marginal means for beauty and realism rating scores by map. Scores were statistically similar between beauty and realism.
also a significant interaction effect between the shaded relief layers and the thematic layers for landform clarity ratings for all three landforms: Wizard Island, Mount Scott, and Grouse Hill, which we did not find for beauty and realism. This meant that there were unique outcomes for user perceptions of landform clarity depending on the pairing of shaded relief and thematic layers. This is an interesting finding because it suggests that shaded relief and specific thematic terrain layer pairings were more important for landform clarity than they were for beauty and realism in our study.

In terms of shaded relief on its own, depending on the landform in question, there was a different order of most to least clear shaded relief layer. Grouse Hill and Wizard Island both had the same, statistically significant order of perceived clarity: multidirectional shaded relief was the highest rated, ray-traced relief was second, and manual relief was the least clear. However, for Mount Scott, von Allmen’s manual relief was the least clear, but there was no statistically significant difference between the two analytical shaded relief methods.

The effect of the thematic terrain layers on landform clarity ratings was also inconsistent across the three landforms, and not always a significant influencing factor. For example, the thematic terrain layers had an influence on clarity ratings for Wizard Island and Mount Scott, but not for Grouse Hill. This finding confirms that shaded relief had a stronger impact on each landform, since statistically we did not find that the thematic terrain layers played a significant role in influencing landform clarity on their own.

The results of statistically testing the interaction of combining shaded relief and thematic terrain layers was significant and provided insights into designing terrain maps with the goal of more clearly depicting landforms to map readers. In short, the differing combination of shaded relief and thematic layers led to different ratings of landform clarity, and this was dependent on the specific landform. For instance, with Mount Scott, landform clarity was highest when multidirectional relief was paired with land cover, but when multidirectional relief was paired with orthoimagery the clarity was negatively affected. This was not the case for Grouse Hill and Wizard Island. For those two landforms, while the interaction effect was still significant, the pairing of the thematic terrain layers with multidirectional relief did not lead to such a dramatic effect on landform clarity. The interaction effect was interesting because shaded relief is rarely used in isolation, and it was clear that the thematic terrain layers had an effect depending on how they were paired with the shaded relief layers. This confirms that neither shaded relief nor thematic terrain layers are the sole contributor to a beautiful, realistic, or clear terrain map, but that the layers provide distinct qualities, and the interaction between shaded relief and thematic terrain is of importance for landform clarity, specifically.

Finally, the results of the landform clarity section of the user study experiment imply that figure-ground may be a confounding factor in landform clarity. For example, Wizard Island had the highest grand mean value for perceived clarity (\(M = 3.90\)), with Mount Scott following (\(M = 3.74\)), and Grouse Hill with the lowest (\(M = 3.62\)), suggesting that map readers on average found Wizard Island to be clearer than the other landforms. It is easy to see when looking at a map of Crater Lake, Oregon that, indeed, Wizard Island is a very prominent feature in the water-filled crater, followed by Mount Scott, the largest mountain landform in the vicinity, followed by Grouse Hill, which is far less visually prominent. It’s understood that there is a special relationship between land and water regarding map interpretation (Head 1972) and that foreground features move up higher in the visual order (Haber and Hershenson 1973). This is especially true when foreground features have greater visual contrast (like the contrast between Wizard Island and the water of Crater Lake) which can help them stand out, become more distinguishable, and create a perceptually distinct sense of hierarchy (MacEachren and Mistrick 1992). The lower clarity scores for Grouse Hill, on the other hand, can be explained by these same theories. Indeed, one participant said that Grouse Hill “was [the] hardest to make clear” which was perhaps because of its lower elevation, minimal vertical height difference, and less contrast between the landform and the base of the hill. While the aim of this research was not to understand the connection between landform clarity and contrast, this result indicates that certain landforms might assume higher landform clarity ratings, regardless of their shaded relief and thematic terrain pairing, because of their figure-ground relationship.

**GEOGRAPHIC FAMILIARITY**

It is known that a person’s landscape preference (Dearden 1984; Herzog et al. 2000) and map reading ability can depend on their prior level of geographic knowledge (Kaplan...
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In this study, familiarity with Crater Lake, Oregon had a statistically significant impact in four specific instances in the user study. Participants who had never heard of Crater Lake were more likely to find Wizard Island to be most clear when multidirectional shaded relief and hypsometric tinting were combined. Interestingly, those who had seen photos and maps of Crater Lake rated Wizard Island as most clear when multidirectional shaded relief was combined with land cover instead. Those same participants were also more likely to rate the combination of multidirectional shaded relief and hypsometric tinting as most realistic. And finally, those who had visited Crater Lake were more likely to rate Mount Scott as most clear when von Allmen’s manual relief was combined with orthoimagery.

CONCLUSION
Cartographers often combine shaded relief with thematic terrain layers when creating terrain maps, thus the primary aim of this research was to understand the relationship between these two layers on map reader perceptions of beauty, realism, and landform clarity. In an exploratory online user study experiment, we tested the combination of three shaded relief layers (manual, multidirectional, and ray-traced) with three common thematic terrain layers (hypsometric tinting, land cover, and orthoimagery) in a series of maps of Crater Lake, Oregon and measured participant’s ratings of beauty, realism, and landform clarity.

OVERVIEW OF THE FINDINGS
There were five main findings in this research which we summarize here.

First, the results of this research showed there to be a direct correlation between beauty and realism scores, which were more influenced by thematic terrain layers than by shaded relief. Cartographers have long suggested a connection between beauty and realism, claiming that a realistic cartographic representation of the landscape can lead to a more appealing aesthetic (Harvey 1980; Robinson 1989), and our empirical research corroborated those claims. Given this, cartographers should keep in mind the link between these two aspects when designing terrain maps.

Second, we found von Allmen’s manual relief to be consistently rated lowest for beauty, realism, and landform clarity, while orthoimagery was rated as most beautiful and realistic, and—when combined with certain shaded relief layers—sometimes improved landform clarity scores. These findings are surprising because, in general, professional cartographers hold manual relief in high regard. They promote it as a beautiful hand-drawn artform (Imhof 1982; Brassel 1974; Collier, Forrest, and Pearson 2003; Marston and Jenny 2015), while orthoimagery is often dismissed as being pedestrian and adding unnecessary visual complexity to maps (Hoarau, Christophe, and Mustière 2013; Touya, Hoarau, and Christophe 2016). This finding may suggest that cartographic experience affects a person’s preferences, however, we cannot make any generalizing claims, given that we only tested novice map users and only used one example of hand-drawn shaded relief.

Third, in contrast to beauty and realism, the landform clarity ratings showed that shaded relief was more influential than the thematic terrain layers; however, there was a significant interaction effect, which meant that different landform clarity ratings arose from different combinations of layers. This is important because past research has focused largely on analyzing map reader perceptions of shaded relief on its own (Biland and Çöltekin 2017; Farmakis-Serebryakova and Hurni 2020; Jenny et al. 2020); however, this research makes it clear that every map has its own unique effect, based upon the combination of shaded relief and thematic terrain layers.

Fourth, a participant’s familiarity with Crater Lake did not influence the overall combined rating scores for all nine maps, but only had a statistically significant impact in four specific instances in the user study. The findings suggest that different levels of familiarity influence reader perceptions depending on the question being asked and the specific combinations of shaded relief and thematic terrain layers.

Finally, in our study, neither shaded relief nor thematic terrain layers were the sole contributors to map readers’ perceptions of beauty, realism, or landform clarity. Instead,
these layers had distinct effects in different situations depending on their pairing. This confirms that the interaction between shaded relief and thematic terrain layers is an important consideration when creating terrain maps.

**LIMITATIONS AND FURTHER RESEARCH**

Future research would be well served by building on the following limitations of this study:

1. While participants consistently rated von Allmen’s manual relief as the least beautiful, realistic, and clear in depicting landforms, the particular drawing used in this study was just one example of this relief method. The look of a manual relief varies depending on the cartographer’s style, skill level, and interpretation of the landscape. Additionally, both the land and bathymetric landforms in von Allmen’s relief of Crater Lake were less detailed when compared to the digital relief models, which may have led to confounding effects on aesthetic perceptions between the different relief methods. Further research should verify these findings by testing multiple manual shaded relief drawings (Jenny et al. 2020), multiple geographies and landform types (Farmakis-Serebryakova and Hurni 2020), varying spatial scales, and different levels of detail.

2. This study did not consider contrast, lightness, or saturation, which may have had confounding effects on the results. The analysis showed that participants felt orthoimagery was the most realistic and beautiful; it was also the darkest, had the highest contrast, and the most saturated colors. One participant commented: “I noticed I liked the darker contrasted maps better than the lighter colored ones.” Likewise, the maps that had the lowest ratings used hypsometric tinting, which was significantly lighter and less saturated. Other cartographic research has shown that map readers’ preferences are strongly affected by contrast (Fabrikant et al. 2012; Limpisathian 2017; Brewer 1992). Future research should emphasize consistency in contrast, lightness, and saturation in terrain representation to avoid this potentially confounding variable.

3. In this research we only tested maps of one location. However, Raposo and Brewer (2014) found that map location and the types of landforms present in the stimuli played a significant role in readers’ aesthetic preferences. Future research could involve showing participants maps of a variety of locations, such as in Jenny and Patterson (2021), manual relief from shadedreliefarchive.com, or using different landforms such as in Farmakis-Serebryakova and Hurni’s (2020) experiment to either corroborate or challenge the findings of our exploratory research.

4. The results of this study also implied that the visual contrast of a landform may have been important in explaining why certain features were consistently rated higher for landform clarity than others. In this study, Wizard Island, arguably the most prominent feature in the Crater Lake area, was consistently rated as the most clearly distinguishable landform, while Grouse Hill was rated as the least clear. Since it is understood that land-water representation has a strong effect on map reader interpretation (Head 1972), there could be a correlation between Wizard Island’s higher visual contrast and higher landform clarity ratings. Future research should control for or test the implications of contrast and figure-ground on ratings of beauty, realism, and landform clarity.

5. Participants noted, in the open-ended question, that seeing one map at a time lead to difficulty in judging the beauty and realism across all nine stimuli maps. Future experiments could involve allowing participants to see all or some of the map designs side-by-side when rating beauty and realism.

6. This research was conducted online and was limited to participants in the United States who did not have expert knowledge in cartographic design. Several potentially confounding variables should be controlled for or explored in future research. Perceptions of clarity and beauty might differ between participants using different screen sizes or digital devices; Between participants given digital or paper maps; between participants in different parts of the world; and between novice participants and experts or practicing cartographers.

7. Participants were only asked to rate the beauty and realism of each map and comment on the clarity...
of landforms. Future research could build upon our exploratory findings to also incorporate tasks that would require participants to interpret large and small landforms, engage in way-finding and navigation, or read overlaying vector information, all in order to investigate map reader performance (Castner and Wheate 1979; Hegarty et al. 2009; Raposo and Brewer 2014; Smallman and St. John 2005).

8. Finally, our research focused on just three shaded relief layers and three thematic terrain layers. Future researchers could expand on this by testing a wider range of layers or a range of parameters used to create these layers. Some examples of terrain map representation techniques to include in a future analysis are: texture shading (Brown 2014), neural network relief shading (Jenny et al. 2020), sky models (Kennelly and Stewart 2014), sky-view factor hillshading (Zakšek, Oštir, and Kokalj 2011), aerial perspective (Jenny and Patterson 2021), 2D versus 3D relief representations (Taveras 2018), plan oblique relief (Jenny and Patterson 2007), and Swiss-style color relief shading (Imhof 1982; Jenny and Hurni 2006).

**CONCLUDING THOUGHTS**

Maps are not just tools for navigating when we get lost, but also works of art worth getting lost in (Ribeiro and Caquard 2018; Harmon 2009). Perceived beauty and realism, in combination with assurance that map readers can accurately see specific landforms, is essential for producing a successful terrain map. With this in mind, our exploratory research provides cartographic researchers with a methodology for investigating aesthetics and landform clarity in terrain maps, with mindful consideration to both traditional and contemporary shaded relief methods when combined with thematic terrain layers. While the results of our research might imply some best practices, we cannot make any definitive claims that can be generalized outside of this study, due to the limitations addressed above. Given this, we encourage future researchers to build upon our work, and provide some helpful insight by further testing the combination of relief and thematic terrain layers.

**REFERENCES**


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