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N. Elmqvist, M. Hlawitschka, and J. Kennedy (Editors)

Short Papers

Color and Uncertainty: It is not always Black and White

S. Tak[1,2] and A. Toet[1,2]

[1]TNO, Soesterberg, the Netherlands
[2]Utrecht University, Utrecht, the Netherlands

Abstract

To fully comprehend the meaning and impact of visualized data it is crucial that users are able to perceive and comprehend the inherent uncertainty of the data in a correct and intuitive way. Data uncertainty is frequently visualized through color mappings. Previous studies argued that color hue is not suitable for communicating uncertainty because most hue scales lack an intrinsic perceptual order. In this paper we examine the use of hue for communicating data uncertainty in more detail. We investigated the potential of distinct color triples (rather than the entire spectrum of colors, as used in previously studies) to represent different levels of uncertainty. We identified several color triples that reliably map to an intuitive ordering of certainty. Bipolar color scales constructed from these color triples can be used to communicate uncertainty in visualizations, particularly to audiences of non-specialists. A 'traffic light' configuration (with red and green at the endpoints and either yellow or orange in the middle) communicates uncertainty most intuitively.

Categories and Subject Descriptors (according to ACM CCS): H.5.m [Information Interfaces and Presentation]: Miscellaneous—

1. Introduction

Uncertainty is often inherent in visualized data, due to errors in the data acquisition and processing phases, and even the representation process itself [BOL12]. To prevent misinterpretation and inaccurate conclusions, it is crucial that the nature and degree of uncertainty in displayed information is correctly communicated to the user.

Various techniques have been proposed to visualize data uncertainty through the graphical properties of depicted entities, such as blur, sketchiness, transparency, size, texture and color [PRJ12]. In the current study we focus on the use of color (and more specifically hue scales) to represent data uncertainty.

The multidimensionality of color together with the wide range of colors that can be discriminated by the human eye has inspired several methods to visualize data uncertainty through color coding [HWB02, ACK03, LB00]. However, since human perception of color is psychological and physiological, but not physical [Tra91], many proposed color mappings do not effectively convey uncertainty [Riv07], Also, although the use of color (particularly hue) to code categorical data is relatively uncontroversial, there is much less agreement on the use of colors to code quantitative data [SKR99, BT07].

In this paper we first investigate if distinct color triples (with different hue values) can effectively convey uncertainty information. The results of this study show that there are indeed color triples that intuitively map to uncertainty. Bipolar color scales constructed from these color triples [Mor09] can then be used to communicate uncertainty in visualizations, particularly to audiences of non-specialists (e.g. in daily weather forecasts [HP07]).

This paper is structured as follows. First we discuss previous work on the capability of color mappings in general, and hue scales in particular, to convey uncertainty. We also address issues related to the cognitive and psychological effects of color connotations. Then we present an experiment in which we identified several color triples that intuitively map to the concept of uncertainty. Finally, we present our conclusions and some suggestions for future work.

2. Related Work

In this section, we give an overview of relevant previous work on using color to visualize uncertainty, color connota-

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tions (i.e., color meaning) and the relationship between color and affect.

2.1. Visualizing Uncertainty through Color

Data uncertainty is frequently visualized through color mappings [DPL*11, BZH11, CBDT11]. Color enables the visualization of data uncertainty without obscuring or distorting the data itself. Since color is inherently three-dimensional, it allows visualizing multiple aspects of uncertainty (e.g., second [DKLP02] and even third order [LKP03] uncertainty statistics).

The obvious and natural psychological dimensions of color are hue, saturation, and lightness or brightness. Lightness and saturation can effectively convey uncertainty, since they correspond to perceptually ordered continuous mappings. Hue lacks an inherent perceptual order and has therefore typically been discarded as an effective representation of uncertainty.

Lightness is a color attribute that intuitively maps to certainty: research has shown that lightness can indeed reliably encode ordered data [SKR99], and lighter features are typically perceived as more certain than darker features [ACK03, LB00, DAN12]. Color lightness or saturation can for instance be used to depict uncertainty on maps in which different hues are used to represent the data values of interest (e.g., on a land cover map).

Color saturation can also be used to convey uncertainty because a reduction in color purity intuitively corresponds to degraded data quality or increased uncertainty (faint colors are associated with high uncertainty) [MRH*05]. However, in practice saturation coding is often not very effective [LB00, MBP98, Dre02] and inferior to brightness coding [War88], although this may be task-dependent [SZB*09]. In addition, equally saturated color hues do not appear equally certain, so that perceived uncertainty varies non-linearly with hue [BZH11].

Hue scales (particularly rainbow or spectral scales [BT07]) often lack an intrinsic perceptual order, and are therefore considered unsuitable to represent ordered data. Moreover, bipolar hue scales (with two hues forming opposing extremes) usually have a non-monotonous lightness order (minimal brightness and maximal saturation in the middle of the scale) that conflicts with their hue order.

Bisantz et al. [BSP*09] investigated display characteristics related to color (hue, brightness and transparency) for displaying various data aspects, including uncertainty. They used three different sets with either 4, 8 or 12 color hues. They asked their participants to order and rate color hues according to latency (age) or probability of the displayed information. They found that color saliency affects order judgments: more 'intense' or salient (darker, more saturated) colors are more often ranked and rated as more certain. At the same time, there is little consistency between participants with regards to how they rank and rate the various color hues. In addition, the direction of the order assigned by the participants depends on background contrast (and thus color saliency) and task relevancy: color hues that contrast most with the background (that are most salient) are assigned to levels of high uncertainty when the task requires focusing on uncertainty, and they are mapped to levels of high certainty when the task involves judgments on certainty. Hence, task relevancy appears to determine the polarity and color saliency the magnitude of color uncertainty ratings. However, other studies have shown that people can reliably map uncertainty to respectively blue (low uncertainty) to red (high uncertainty) [HM96] and green-red [RLBS03] hue scales. For green (low uncertainty) to blue (high uncertainty) people find it hard to estimate uncertainty [NL04].

Because the effectiveness of hue for communicating uncertainty is still undecided, we investigated this issue here in more detail.

2.2. Color Connotations

It is generally found that phenomena visualized in ecological or natural colors (i.e., colors close to the viewers' experience with those phenomena) appear more intuitive and require less cognitive effort to understand. In thematic maps blue colors are therefore often used for the illustration of water depths or wave heights, green colors for vegetation (meadows or forests), brown for earth types (mud, sand), white for snow etc. [KK93].

Studies have shown that people identify red and yellow colors as 'warm' and blue and blue-green colors as 'cool' across subjects, contexts, and cultures. Furthermore, people associate warmth with positive activation and coolness with negative activation [HM97]. Consequently, mapping cool blues to low values and warm reds to high values intuitively appears natural [FM97]. As noted before, hue scales generally lack a natural ordering. Information about these known 'opposing' color connotations can be used to create bipolar scales, which inherently impose an ordering on color. An intuitively ordered color scale can be obtained by carefully selecting the two endpoints of a bipolar color scale such that they have respectively 'low' and 'high' connotations [Mor09]. This can for instance be achieved through the concept of 'cool' and 'warm' colors.

Color has also extensively been studied in the context of warning signs and risk perception [WCSJ02]. There appears to be a distinct risk hierarchy for color: red is perceived as riskier than yellow, and yellow as riskier than green [SJW00], while blue is frequently associated with security and comfort (low risk) [Wex54]. Thus, mapping green or blue colors to low uncertainty and red or orange to high uncertainty may yield an ergonomic color mapping for uncertainty.

3. Experiment: Tricolor Sets

Though earlier results [BSP*09] would seem to argue against the use of color for representing uncertainty, we feel that this can be attributed to the large number of distinct color hues used in that study (in their conditions with 8 and 12 colors) and the lack of a natural perceptual order in their condition with 4 hues (red, blue, green, yellow). Although hue may well be locally ordered it lacks an intuitive overall perceptual order. As a result, the likelihood of finding an intuitive order decreases with the number of distinct colors. Hence, triples are more likely than 8/12 tuples to have an ordinal quality (e.g., to fall along a curve in the color space). [BSP*09] found indeed that observers prefer a smaller number of different colors for the display of meta-information on a map background. This may reflect working memory limitations: when there is no inherent order in the set of colors people need to memorize the assigned order. When the number of levels exceeds the typical working memory span people may experience difficulty remembering previously assigned color ratings.

Here we hypothesize that more intuitive orderings can be made with the use of only three colors. In addition, when the two outer colors are primary and the middle one is a secondary color which is a 'mix' of the two outer ones (e.g., blue-purple-red) a continuous bipolar spectrum can be generated [Mor09]. This allows for an acceptably high level of granularity when the range is used to represent a certain variable, such as uncertainty (see Figure 1). To test this hypothesis we performed an experiment to identify color triples with an intuitive link to uncertainty.

Figure 1: *A yellow-orange-red spectrum.*

3.1. Method

We used the six primary and secondary colors as shown in Figure 2. The colors were chosen such that they have equal saturation and lightness values in the HSL color system, i.e., only the hue was varied: S=255, L=128, H red=0, orange=21, yellow=43, green=85, blue=170, purple=202. The colors were presented in three circular patches with equal diameters, vertically arranged on a white rectangular background (see Figure 3).

We note that by using colors with equal saturation and lightness in the HSL color space, the perceived brightness (or luminance) is not equal (e.g., yellow will look much brighter than blue). As a result, the visual saliency of the colors may differ. However, we chose not to correct for this effect for two reasons: *(1)* for these six color hues is impossible to create a set with equal luminance whilst retaining a reasonable approximation of the hues (the yellow and orange in particular will become brownish) and *(2)* the fact that colors differ in terms of perceived brightness is also the case in real life. Hence, adjusting for perceived brightness affects the ecological validity of the study.

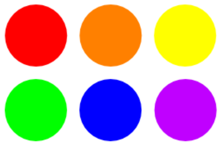

Figure 2: *The six experimental colors.*

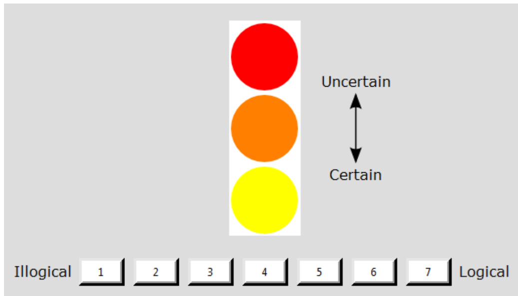

Figure 3: *The trial interface.*

3.1.1. Pilot Experiment

Using six color hues in sets of three colors means that 6×5×4 = 120 different color sets can be generated, where half of the sets are mirrored version of the other half. As the use of all 120 sets would make the experiment prohibitively lengthy, we performed a pilot study to assess which of the color sets could be regarded as having at least *any* kind of perceptual order. After all, sets without any intuitive perceptual order are typically not suitable to represent an (un)certainty order.

Three non-colorblind participants (2 male, 1 female, ages 22, 31 and 63 years) viewed all 120 sets of three colors in random order. For each set, they were asked to indicate (*yes/no*) whether they thought the set was ordered. The instructions stated that the meaning of the order (if there was any order) was irrelevant. In other words, it did not matter what the order represented (e.g., large to small, high to low, unimportant to important).

Each set that was judged to be ordered by at least two out of the three participants was used in the main experiment. Also, all mirrored versions of the sets were included. This resulted in a total number of 62 ordered sets (31 unique sets and their mirrored versions).

3.1.2. Main Experiment

Each session began with a descriptive overview of the experiment purpose, explaining that graphical representations (e.g., line graphs with temperature forecasts) nowadays often include a representation of uncertainty, but that it is not yet known how to select appropriate and intuitive color schemes to represent uncertainty. Participants were asked to rate the degree of logic/intuitiveness of each color triple as a representation of uncertainty on a scale of 1-7 (see Fig. 3). We also registered their response time. This paradigm and stimulus layout were similar to those used in an earlier study [MRO*12]. In addition, we included open questions at the end of the experiment, asking the participants *(1)* to reflect on the strategy they used to assess if a color triple had an intrinsic perceptual order and *(2)* which colors they judged most appropriate to represent (un)certainty. We recruited 21 participants (13 males, 8 females, aged 16-56, mean age 28.4, with various educational backgrounds) and showed them (in random order) all 62 color triples that were identified in the pilot experiment as potentially having an intrinsic perceptual order.

3.2. Results and Discussion

For the 62 sets used in the experiment, we found a significant effect of color set on intuitiveness (Kruskall-Wallis, p<.001), but no effect on response time (one-way ANOVA). The absence of an effect on response time suggests that participants found the task equally easy/difficult regardless of the particular color set shown. The significant effect of color set on intuitiveness indicates that some color sets are regarded as more intuitive for representing uncertainty than others. In response to the open questions several comments were repeatedly made (# = number of participants):

- red and orange are most suited for uncertain information (14),
- green is most suited for certain information (9),
- lighter colors are less certain (7),
- a traffic light configuration (red, orange, green) is very suitable for representing uncertainty (4).

Figure 4 shows the five color triples with respectively the highest and lowest (mean) scores. From this figure, several observations can be made:

1. a 'traffic light' triple (red, orange/yellow, green) scores best, regardless of whether the middle color is orange or yellow,
2. the intuitiveness of the mapping of yellow can be reversed completely depending on the context; yellow represents uncertainty when it is shown together with green and blue, but it represents certainty when it is shown together with orange and red,
3. orange is unsuitable for representing certain information.

The explanation for finding (1) is that the 'traffic light' color triple is a well-known configuration and an intuitive anal-

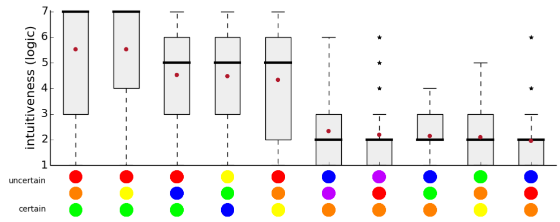

Figure 4: *Tukey boxplot of the five highest and the five lowest scoring color sets on intuitiveness rating. Thick lines denote the medians, red dots denote the mean, and stars denote outliers (values more than 1.5 IQR below the first quartile or above the third quartile.*

ogy for (un)certainty. Uncertain information usually means that some restraint is in order (i.e., 'wait'), while green implies that everything is OK (i.e., 'go'). Finding (2) suggests two underlying mechanisms in action. The open questions revealed several factors that determine which color sets are more or less intuitive for representing uncertainty; red is uncertain, green is certain, and lighter colors are more certain. For the yellow-orange-red set (where yellow most intuitively maps to certainty) the role of red seems to be crucial; while for the yellow-green-blue set (where yellow most intuitively maps to *un*certainty) the (perceived) lightness is probably the deciding factor (as noted earlier, in the color sets used in the current study yellow had a higher perceived lightness than blue). Finally, finding (3) can probably be attributed to two factors. First of all, people seem to prefer red, blue, green or yellow as the end points of the scale, but not orange or purple, probably in part because the latter two are secondary colors. It seems logical to use two primary colors as end points, with the appropriate secondary color in between. Second, orange is close to red in the color spectrum, and many people indicated that they considered red to be a poor choice for representing certain information.

4. Conclusion

We found a significant effect of color set on intuitiveness: some color triples are regarded as more intuitive for representing uncertainty than others. A 'traffic light' configuration (red, orange/yellow, green) scores best, while the connotation of yellow depends on its context (the other members of the triple), and orange is only associated with uncertainty (but not with certainty). Intuitively ordered color triples may be useful for uncertainty visualizations, particularly when these are aimed at non-specialists.

In a future study we plan top investigate *(1)* the effect of background contrast [BSP*09], and *(2)* the cognitive connotation between a visualization and its color setting on perceptual color order judgments.

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