Beautiful Visualizations Slain by Ugly Facts:

Redesigning the National Hurricane Center's 'Cone of Uncertainty' Map

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ABSTRACT

The Track Forecast Cone, commonly known as the “cone of uncertainty”, is the most popular hurricane and tropical storm forecast product that the National Hurricane Center produces. However, it is often misinterpreted by non-experts. In this study we first explored the most common misconceptions about the cone and produced two alternative redesigns that we expected to be more attractive to and easier to understand by non-expert readers. Our results were mixed, but reveal promising paths for future efforts.

Index terms: Uncertainty, Data visualization, Forecast visualization, Graphical literacy.

1 INTRODUCTION

The great 19th century defender of Charles Darwin's theory of evolution by natural selection Thomas Henry Huxley once said that the great tragedy of science is “the slaying of a beautiful hypothesis by an ugly fact.” [9] We feel that a similar claim can be made about visualization design: no matter how well made and beautiful a graphic is, no matter how much it follows rules and conventions [8], it will often be “slain” when tested against the reality of its readers. This paper tells such a tale.

According to metrics provided by the National Hurricane Center's (NHC) [12], its Track Forecast Cone product, commonly known as the “cone of uncertainty” (COU), is the most viewed graphic on the NHC website. The map is commonly used by TV stations and other media organizations [10], and it often appears in social media communications by the NHC and news media.

The cone (Figure 1) represents the uncertainty around the forecasted track of a storm center. As the NHC explains, “the cone represents the probable track of the center of a tropical cyclone, and is formed by enclosing the area swept out by a set of circles (not shown) along the forecast track (at 12, 24, 36 hours, etc.) The size of each circle is set so that two-thirds of historical official forecast errors over a 5-year sample fall within the circle” [13] Among the many elements contained in the COU is this warning— “The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone” [7].

The COU is a product designed to be consumed mainly by an audience of experts—forecasters, risk managers, and other

decision-makers—and not directly by the public [13]. This has led to many types of misinterpretations that have been well documented in the academic literature [3, 19]. The most common misinterpretation, particularly among inexperienced readers, is to see the cone as an enclosed area under threat rather than a representation of uncertainty.

Figure 1: NHC cone of uncertainty (COU) product

Reports have also pointed out that “too many people place undue confidence in the forecast track of the storm” [21]. Various researchers and designers have attempted to come up with alternative ways to reveal the probable paths of a storm center and other relevant information [6, 11, 18, 20], while others have studied whether explaining the conventions used on the COU improves reader understanding [1].

Other elements on the COU other than the cone itself, such as color palettes and labeling, have received little attention from researchers. The COU uses a categorical, non-sequential color palette to identify coastal areas under watches (possibility of being at risk in the next 48 hours) and warnings (danger of being affected by storm surge, winds, and other threats in the next 36 hours) [16]. It also categorizes sustained wind speeds with letters: D for tropical depression (<39 mph), S for tropical storm (39-73 mph), H for hurricane (74-110 mph), and M for major hurricane (> 110 mph). However, the graphic does not include a legend that explicitly explains what those letters mean; to find this information, readers must consult documentation in the NHC website [14]. Moreover,

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for non-specialist readers, the COU may not be very useful, as it does not present information about storm-related hazards, such as strong winds, heavy rain, and storm surge. For these readers, the forecasted track of the center of the storm, and the uncertainty around it, are poor indicators of potential hazards.

2 GOALS OF THE STUDY

In this study we explored how design elements influence interpretations of hurricane risk, we compared non-expert responses to the cone of uncertainty against two new forecast graphic prototypes, Redesign A and Redesign B, each modifying elements of the COU to address common misinterpretations. We considered how visual appeal influences preferences and perceptions of the NHC's COU in comparison to the two alternatives.

3 METHODS

3.1 Interviews

We recruited students from the University of Miami to participate in this study. The study was pre-approved by the University of Miami's Institutional Review Board (IRB). We included participants age 18 or older, with the ability to speak and read English. A total of 43 college students participated in the interviews. The 19 male and 24 female participants were between the ages of 19 and 47 ($M = 25.70$, $SD = 6.35$). Most participants (81.4%) had prior experience of living in an area threatened by a tropical cyclone. Interviews were conducted one participant at a time.

The research team explained the purpose of the study to those interested in participating. Those who agreed to take part in the study read the consent form and gave verbal consent. Participants then completed a demographic questionnaire. Names or other personal identifiers were not collected.

During the interviews, participants were shown three visualization prototypes to facilitate discussion and to illustrate alternative representations of specific design elements. The researcher asked participants three questions about each of the visualizations: "What do you like about this visualization?", "What do you dislike about this visualization?", and "What would you change about this visualization?". However, the interviews were semi-structured allowing for additional questions that might arise during the discussion. Participants were also asked to rank the visualization prototypes in order of preference.

The answers from study participants were audio recorded and transcribed into an electronic datasheet for analysis. Descriptive statistics were generated for the demographic information. The qualitative data was processed using content analysis techniques and NVivo software, version 12. Two researchers completed the qualitative analysis. Their work was checked for interrater reliability and validity.

3.2 Prototypes

For this study, we produced three design prototypes using data from historical hurricanes overlaid over a map of the United States, modifying colors, type, and arrangement of the traditional COU. The first design used was the existing COU (see Figure 2), with only minor updates to increase color contrast, highlighting the cone over the ocean and landmass. The traditional COU contains a hard boundary whose distance from the forecast point is calculated

as the 67th percentile of all NHC forecast errors of tropical cyclone track over the previous five years. The inside of the cone is colored white, with the hard boundary represented by a solid black line. This feature facilitates the common misinterpretation that if one is outside of the boundary, one is safe from the storm [6, 13, 19].

We developed two alternative versions of the COU to eliminate the hard boundary. The second design used (see Figure 3), our COU Redesign A, blurred the boundaries of the cone, and employed a uniform, diffuse gray shading. In addition, we added a "How to read the cone" textual explanation above the map that expands on the label the original NHC COU contains ("The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.")

Colors for watches and warnings were also changed to a sequential color palette ranging from light yellow (for Tropical Storm watches) to dark red (Hurricane warnings.) The legend at the bottom of the map in this version added contextual explanations of map abbreviations: M for major hurricane, H for hurricane, S for tropical storm, and D for tropical depression.

Figure 2: NHC cone of uncertainty (COU) product with minor

modifications by the authors

Figure 3: Redesign A

The third design used (see Figure 4), our COU Redesign B, employed different gradations of the diffuse gray shading. Regions closest to the official NHC forecast position were shaded darker, and regions further were lighter. More precisely, the 33rd, 50th, and 67th percentiles of the previous five years of NHC track forecast errors were computed. Circles with a calculated radius for the 33rd percentile were then filled with the darkest diffuse shading, followed by lighter shading for the larger radius corresponding to the 50th percentile, and even lighter shading corresponding to the 67th percentile. This design also modified the COU by depicting separate maps for watches, warnings, and the cone, while also maintaining the changes in the legend and color schemes of redesign A and expanding the "How to read the map" legend.

Figure 4: NHC cone of uncertainty (COU) product with minor modifications by the authors

It is worth noticing that Redesign A and Redesign B were inspired first by a literature review on misinterpretations of

uncertainty, confidence, and hurricane forecast products [12]. Another source was the results of several exploratory focus groups conducted between May 15, 2018 and February 13, 2019, recruited through and held at Centro Mater in Little Havana, Catalyst Miami, and Miami Dade College InterAmerican Campus. In these focus groups, participants—all of them from the Miami, Florida area, and with different degrees of experience facing tropical storms and hurricanes—were asked to discuss their interpretations of the NHC cone map. The results were coded and will be discussed in detail in a future paper.

Participants in the focus groups described how they used NHC cone map, to verbalize the information they extracted from it, and to express difficulties when interpreting its components (labeling, legends, etc.). Moreover, participants were asked to suggest what they thought might make the map clearer, with many of them complaining about the “clutter” of a graphic that, according to them, was trying to stack too many layers of information into a single display. This, for instance, led to one of the decisions on Redesign B: separating the cone from the Watches and the Warnings, and instead devoting one map to each.

4 RESULTS

4.1 Rankings

The mean ranks for forecast graphic design were 1.81 for the NHC design, 2.07 for the Redesign A, and 2.12 for the Redesign B (a lower mean rank is better- closer to first place). The NHC design received the most first-place votes (19/43). Analysis with a Friedman test showed no significant effect of design on preference ($X^2(2) = 2.279$, $p > .05$).

Figure 5: Visualization design rank

4.2 Discursive Responses

Our interviews revealed some of the factors that influenced participants' graphic preference and interpretation (Figure 6). Cone design was a primary reason for top choice selection across the three graphics. Other factors included treatment for watches and warnings, familiarity, color scale, legend, and visual design.

	NHC	Redesign A	Redesign B
1	Cone design (18/19)	Cone design (7/11)	Separate maps for Watches and Warnings (7/13)
2	Color scale (8/19)	Color scale (5/11)	Cone design (6/13)
3	Familiarity (6/19)	Legend (4/11)	Visual design (4/13)

Figure 6: Most frequent reasons offered for first choice selection. Reasons coded by investigators.

4.2.1. Representation of Path Uncertainty - The Cone Design

Of the 19 participants who selected the NHC graphic as their most preferred, 18 indicated that their preference was because of the cone design. Specifically, that the cone (filled in white and outlined with a black border) had high visual saliency and drew their attention to the focal point of the graphic. However, it is important to note that when describing what the NHC cone conveys, of the participants providing interpretations, all five provided erroneous interpretations, such as indicating that the black border bounds the impact of the storm, contains all possible storm paths and offers certainty about where the storm begins and ends.

Although the cone design was the top reason for participants' first choice of the NHC graphic, cone design was also important to those who selected Redesign A (11) and Redesign B (13), albeit to a lesser extent (63% and 46%, respectively). Participant responses included both correct and incorrect interpretations. The incorrect interpretations of the shaded ("fuzzy") cone, used in Redesign A and B, included that a fuzzy boundary implies that the warning is less urgent and indicates that the further you are from the center of the cone, the less likely you are to feel storm effects. Correct interpretations noted that the shading depicts probability that the storm can pass outside of the cone. For the Redesign B design in particular, a few participants indicated that the shaded cone with the gradient did a better job of conveying the uncertainty in the forecast and eliminated "a false sense of security".

4.2.2. Watches and Warnings

Initial research efforts [12] suggested that the watch and warning map overlay contributed to information overload. Hence, Redesign B separated watch and warning information from the cone. Of the 13 participants who selected the Redesign B visualization as their most preferred, 7 explained that presenting the watches and warnings separately influenced their preference. For some, the separation of information better highlighted coastal areas under threat. However, many more participants (10) indicated that overlaying the watches and warnings was critical in storm path estimation, suggesting that understanding the forecast was dependent upon watch and warning information.

4.2.3. Familiarity

When selecting the NHC as their preference, participants indicated that familiarity with the graphic played an important role. Representative participant voices:

"This is my favorite because it is the one I see the most. I'm most familiar with it. This is the one I always see when there are hurricanes."

"I prefer the NHC because it's the one that I'm most familiar with. I've always seen that. I'm comfortable with it."

However, the perceived cognitive ease in processing familiar representations of information did not lead to better understanding (see 4.2.1.)

4.2.4. Color scale

In all three visualizations, watches and warnings for hurricane and tropical storms are encoded with color and overlaid on a map. However, participants found the use of a gradient color palette to convey categories of storm and alert types problematic, specifically the use of the sequential, warm palette ranging from yellow to red in the Redesign A visualization. Many participants (5) observed that the color palette did not provide sufficient discrimination between a tropical storm warning and a hurricane watch, making it difficult to see the differences. As a

result, participants (7) preferred the NHC's use of *distinct* colors to convey storm and alert categories. Participants did not identify the color scale used in Redesign B as problematic possibly because different colors were used to convey the storm categories, while separate maps conveyed each alert type.

4.2.5. Layout

Eleven participants expressed dissatisfaction with the Redesign B visualization layout. In particular, participants indicated that the Redesign B visualization had higher visual search demands because of the absence of visual hierarchy, related information was not grouped together, and there were additional data elements to process. Some participants (6) felt that Redesign B took more time to process as the layout lacked hierarchy, not guiding the eye to design elements based on their relative importance. Therefore, the layout was unclear, with design elements sequenced without apparent reason, making the message difficult to discern. Five participants also noted that the Redesign B visualization had twice as many design elements (6) to process than the other two visualizations, increasing the complexity of the visual representation of the information. Furthermore, the arrangement of the elements in Redesign B placed related items distally. For example, the "how to read map" component was placed in between the advisory information and the legend for the forecast wind speed. Participants explained that because the advisory information and forecast legend were related, they should be grouped together.

4.2.6. Legend

A common criticism of the NHC visualization was that it did not provide precise labeling of storm categories. The map has icons representing types of storm (e.g. H for Hurricane, M for Major Hurricane, D for Tropical Depression), but the legend does not disclose the meaning of the letters. Regarding Redesigns A and B, participants appreciated that the legend provided matching and contextually relevant information of the storm characteristics.

4.2.7. Visual Design

We define visual design as the aesthetics of a visualization characterized by use of images, fonts, color, and other visual elements. Participants often commented that the NHC visualization looked "dated". Likewise, participants appreciated the modernized visual treatment in Redesigns A and B. Nonetheless, participants did criticize some design elements for the "modern" visualizations. For the Redesign A, participants felt that the "shaded" cone lacked sufficient contrast to the map background, impeding assessments of forecasted storm path. For the Redesign B, the smaller font size hindered text readability.

5 DISCUSSION

The results of our study cast light on the interplay between several factors that designers often consider when designing a visualization to be consumed by the general public [4, 17]: familiarity, personal taste, effectiveness—how successful a graphic is at communicating its intended message,—and perceived complexity.

5.1 Familiarity drives preference

We observed that familiarity is a driver for preference, confirming previous studies [2] that report that repeated exposure to a stimulus increases the likelihood of choosing that stimulus over others. However, what people claim to prefer to see is often not what works best for them. Repeated exposure doesn't lead to better interpretations. Familiarity might inflate reader confidence without increasing understanding.

When given the choice between the original NHC COU, Redesign A, or Redesign B as a graphic to see when a tropical cyclone is approaching, a plurality of our participants chose the NHC COU, and sentiments in favor of this choice against Redesigns A and B were strong. Nearly all of these participants mentioned the visual salience of the cone (distinctive fill color, sharp and very visible black boundary) as a factor for the choice, and one third mentioned familiarity. The alleged reasons to mention the salience of the cone were that it provides a strong focal point, it is easier to see than when it has fuzzy or blurred boundaries, and it draws attention to the display.

However, participants who mentioned the cone design and its salience as the deciding factors were asked about what the cone represents. All of them misinterpreted the cone as an area at risk, not as a display of confidence and uncertainty. This is one of the most well documented misinterpretations of the cone [3, 10, 12].

On the other hand, participants who selected Redesign A or Redesign B—both with a cone that has a fuzzy boundary, rather than a sharp black boundary—as their first choice correctly interpreted the cone, and pointed out that blurring its boundary was a good solution to suggest uncertainty about the position of the storm center in the following days.

Among the limitations of this case study is that we did not include assessments of graphical literacy in this analysis. It might well be that readers with higher visual literacy are more comfortable with displays of uncertainty, and therefore do not reject them on the basis of personal taste or familiarity.

5.2. Preference for certainty

In relationship to the previous point, a key paradox we observed is that participants in our study preferred the NHC cone of uncertainty because they saw it as a more certain depiction of the likely path of the storm. Participants both in this study and in our preliminary focus groups claimed that they prefer more reliable and precise forecasts and hence gravitate to visualizations that they (mistakenly) perceive as containing less uncertainty. This is a key challenge, as completely certain forecasts are impossible: what people want to see (*where the storm is headed for sure*) conflicts with what can be predicted and shown (*the storm might be heading here, or here, or even here.*)

As we explained before, the cone of uncertainty is a product designed to be consumed by scientists, risk assessment managers, and decision-makers [10]; it ended up becoming one of the most popular pieces of information the National Hurricane Center produces in part because it frequently appears in news media [3]. The general public, therefore, is very used to seeing it. Significant changes to its design provoke rejection, so we conjecture that designers might want to be cautious when proposing radical modifications to the COU [18]. Incremental, subtle changes might be more appropriate.

Also, a short-term strategy worth considering by the NHC or news media is to keep using the COU, but systematically pair it with detailed explanations of how to interpret the cone correctly [5]. The NHC itself has produced a short explanatory video about what the cone map shows and *does not* show [15]. In the long term, this strategy might increase general public understanding, as previous studies have found that instructions explaining graphical conventions might help reduce explicit misconceptions about the cone of uncertainty [1].

5.3. Perceived complexity

In the focus groups we conducted prior to creating Redesign A and Redesign B, a common complaint was that the NHC COU is extremely cluttered, as it contains several layers of information that often interfere with each other; the cone itself, indications of wind speed, Watches and Warnings, among other elements, all over a

map depicting the regions surrounding the possible path of the storm center. Focus group participants expressed that they would like to see either less information, or information presented in smaller, sequential chunks.

To address this request, we developed a multi-section layout on Redesign B: one panel for the cone, one panel for each Watches and Warnings, and one panel that explains how to read the cone correctly. While some participants appreciated this layout, a noticeable number also felt that there were too many elements in the display, and that they didn't know where to look, or where to begin reading the graphic. Redesign B seemingly lacked information hierarchy to guide the readers. Moreover, even if some participants liked the language in the "How to read the map" box, they suggested variations to the sorting of its elements to make the information clearer and easier to follow.

Other complaints about Redesign B had to do with the color palettes: we tried to restrict our choices to the same two hues on each of the Watches and Warnings maps: red for hurricane winds (red) or tropical storm winds (orange) in the next 48 hours (Watch) or 36 hours (Warning). Several readers were confused by this choice; they claim to prefer a color palette with more distinctive hues and shades.

Finally, and more importantly, in our study deconstruction did not improve workload for many participants, as they relied on watch and warning information and the cone of uncertainty to estimate storm path. The deconstructed COU layout (Redesign B) forced readers to mentally combine the information across the maps and was perceived to be more time consuming and taxing.

In sum, we strongly expected that our redesigns, particularly Redesign B would be easier to understand—and look more attractive and elegant to readers—by separating the relevant information into several panels, rather than presenting it all at once in a single panel, something that participants in our focus groups said makes the COU map hard to read, cluttered, and confusing. Our results were mixed, to say the least. However, it is unclear if different layouts, better color palettes (with more distinct colors and shades,) or more concise explanatory annotations would make Redesign B more effective. We plan to experiment with this in the future.

6 CONCLUSION

This project describes an exercise on identifying misinterpretations of the NHC COU product, an effort to create alternative versions of it, and the results of a study analyzing readers' responses to them. While our results were mixed, and cannot confirm that the alternative designs were more effective, they provide some promising hints about what future attempts could focus on.

First, designers need to acknowledge that familiarity with an existing graphic will drive readers' preferences, but doesn't increase understanding; quite the contrary, familiarity might lead to overconfidence. They should try to correct for that fact while designing products that look familiar enough not to provoke rejection.

Second, we did find some promising hints that explanatory annotations of how to interpret the COU correctly may enhance readers' understanding. Finally, and based on both on this study and the preliminary focus groups that preceded it, future design efforts may lead us to design products that emphasize hazards and risk, rather than just the possible path of a storm center. A common complaint among participants was that the cone did not provide information of possible threats and, therefore, designers should consider creating visual products that combine the existing "cone of uncertainty" map, including its watches and warnings, with other

maps that reveal the risk of being affected by storm surge, strong winds, flooding, and other factors.

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