

The Impact of Familiarity on Visualizations of Spatial Uncertainty

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While visualization can support understanding complex phenomena, their effectiveness might vary with the recipient's familiarity with both the phenomenon and the visualization. The current study contrasted interpretations of simulated hurricane paths using student populations from a high frequency hurricane area versus no local hurricane risk. Non-expert understanding of trajectory predictions was supported via two visualizations: common cones of uncertainty and novel dynamic ensembles. General patterns of performance were similar across the two groups. Participants from the high hurricane risk area did show narrower decision thresholds, in both common and novel visualization formats. More variability was consistently considered possible when viewing the dynamic ensemble displays. Despite greater likelihood of experiences with variability of trajectories outside of forecast paths, greater familiarity tended towards narrower interpretations of the need for evacuations within the variability possible. The results suggest an advantage of dynamic ensembles in grasping uncertainty even in populations familiar with hurricanes.

INTRODUCTION

The 2020 Atlantic Hurricane season featured a record 30 named storms, with 13 storms reaching hurricane status, 6 of which were major hurricanes (level 3-5 on the Saffir-Simpson Hurricane Wind Scale, with winds in excess of 111 mph). Such storms are a major threat to the coastal regions of the US in the Gulf and Atlantic. Individuals in affected regions must prepare for the potential of enormous disruptions and even possible evacuation. However, the path of an incoming storm is inherently uncertain, and people often struggle to understand these types of spatial uncertainty (Wickens et al., 2020).

One mechanism that attempts to enhance understanding of spatial uncertainty in the case of hurricanes is the use of National Hurricane Center Track Forecast Cones ('cones of uncertainty'), which are frequently used by weather forecasters when conveying information about such storms to the general public (Broad et al., 2007). The cone of uncertainty draws from historical tendencies to capture 2/3 of deviations from the most likely storm track. While these types of visualizations might provide some assistance in interpreting spatial variability (see, for example, Pugh et al., 2018), numerous shortfalls in understanding cones of uncertainty have been highlighted in non-experts viewing them (Boone et al., 2018; Ruginski et al., 2016; Padilla et al., 2017).

Recently a new type of visualization to support the interpretation of hurricane paths was developed - dynamic ensembles (Witt & Clegg, 2021; Witt et al. 2020; see Figure 1). The visualization presents an array of simultaneously moving dots, each illustrating a potential path for the storm. Initial evidence suggested some advantages from dynamic ensembles, particularly in understanding the potential for risk outside of the central currently forecasted path, and in overcoming the containment heuristic (a tendency to view locations falling just inside the cone of uncertainty boundaries as far more likely than those just outside, despite their very similar actual probabilities; see Padilla et al., 2018). Previous research with this new type of tool intentionally used participants with limited knowledge of cones to assess underlying perceptual and decision-making properties without the influence of prior experience.

However, familiarity from prior experience with hurricane forecasts might change the understanding of these

visualizations (Maltese et al., 2015) – either for cones that people will have seen and attended to if they live in high risk hurricane zones, or for novel dynamic ensembles if people from higher hurricane risk areas employ greater knowledge from their prior experiences about the potential variability of trajectories that could inform their interpretations. The current study looked at decisions around simulated incoming hurricanes supported with cones of uncertainty or dynamic ensembles, seeking to explore differences between two student populations: one drawn from a high-risk hurricane area and one from an area with no local hurricane threat.

The University of West Florida (UWF) is a regional comprehensive university in Pensacola serving northwest Florida. Eighty-six percent of UWF students originate from Florida, with 60% from northwest Florida and the remaining 26% coming from other Florida regions (University of West Florida, 2020). Of the 14% of students who attend UWF from out of state, just over half (7.23%) originate from other coastal states (Alabama, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas). Thus, 93% of UWF students come from tropical storm and hurricane prone areas. Within the 2020 season alone, 11 storms made landfall in these eight states (National Hurricane Center, 2020a). In contrast, just 5.07% of undergraduate students attending Colorado State University (CSU) come from these eight states, and Fort Collins is not at any risk from hurricanes, thus providing a sample with much lower exposure to threats from hurricanes or a personal need to regularly attend to hurricane forecasts.

In September 2020 (about 6 months prior to the current data) UWF students experienced forecasts using a cone of uncertainty for Hurricane Sally first hand. The path at 8am on September 12, as the hurricane formed, had a cone of uncertainty that included Pensacola (National Hurricane Center, 2020b). By the forecast at 5pm on September 12, Pensacola was on the boundary of the cone, and by 8am on September 13 Pensacola was just outside the cone. When the hurricane subsequently slowed and unpredictably turned north, Pensacola again fell within the cone. Hurricane Sally made landfall at about 6am on September 16 in Gulf Shores, Alabama about 30 miles west of Pensacola. The impact from this relatively close distance was further accentuated by a high degree of asymmetry, and the strongest winds being on the

eastern (Pensacola) side. Leading up to landfall, there was widespread exposure to cones of uncertainty from social media local news coverage, and local communications from the university, city, and county. Misinterpreting the uncertainty had very real consequences for UWF students, with widespread flooding, wind damage, and major infrastructure disruptions along with 10 days of campus closures.

METHOD

Design. Participants from two cohorts (Colorado, Florida) made evacuation decisions in response to an impending hurricane. The forecast was shown using two types of visualizations (cone of uncertainty; dynamic ensembles).

Participants. Twenty students enrolled in an introductory psychology course at the UWF and 22 students enrolled in an introductory psychology course at CSU received course credit in exchange for completing the experiment through Qualtrics. All self-reported normal or corrected-to-normal vision.

Stimuli. All stimuli were created in R (R Core Team, 2019) and presented in Qualtrics. The map depicted the Gulf coastline of the United States (see Figure 1). Storm predictions were set to a mean angle (50, 70, 90, 110°) with the standard deviation (SD; 10, 20, 30°) corresponding to low, medium, and high prediction uncertainty. The town was displayed on the coastline border as a red circle. Towns were positioned at 1 of 13 locations, ranging from -2 to 2 times the storm prediction's SD. Thus, towns presented at the farthest locations were twice as far out as the storm's SD.

Each storm prediction was displayed with two types of visualizations: the cone of uncertainty and dynamic ensembles (i.e., *zoomies*). The cone of uncertainty was created by connecting two lines with an arc. The lines were positioned at 1 SD of the storm's prediction. Lines originated from a filled circle surrounded by an outline, which signified the storm's current position. Three additional filled circles, connected by lines, mapped the central storm predicted path. The central storm predicted path was oriented to match the storm's predicted angle.

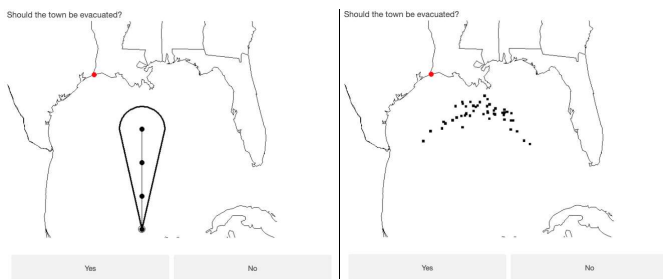


Figure 1. An illustration of a cone trial (left) and dynamic ensemble (zoomie) trial (right). Both trials shown have the same storm angle, prediction uncertainty, and town position. For each trial, only one visualization was displayed. The zoomies traveled from the bottom of the screen towards the coastline. The zoomie display continued to loop until participants responded.

The other visualization condition was the zoomies. The zoomies display was an animated GIF. The zoomies consisted

of 50 small squares that moved towards the coastline from the center of the bottom of the display. Each zoomie followed a linear path at an angle that was determined through random sampling of a normal distribution with a mean equal to the storm angle and SD equal to the storm SD. Thus, most of the zoomies were within 1 SD, but zoomies were also presented beyond 1 SD. A slight jitter was added to the vertical displacement to increase the visibility of the zoomies. The full zoomie movement lasted 60ms, and the animation played on an infinite loop until the participant responded.

Procedure. Participants followed self-paced instructions for both conditions. Instructions for the cone condition were:

“Imagine it’s hurricane season and you are in charge of deciding whether to evacuate a town based on the predicted hurricane path. The town will be marked with a red circle. If you choose not to evacuate the town and a hurricane hits, damage will be extensive and costly. If you choose to evacuate the town and the hurricane does not hit there, money will be spent on the evacuation for nothing. Thus, there are benefits and costs to evacuating the town. Towns must be evacuated 12 hours in advance of when the hurricane will hit. For each decision, a hurricane is hovering and is approximately 12 hours away, so it will be time to make your decision. *You will see a cone that shows the predictions of the hurricane’s path. The cone shows the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.*”

The description of the cone of uncertainty was based on the text presented on the National Hurricane Center website (National Hurricane Center, n.d.). The zoomies instructions were identical, except the italicized part was replaced with: “*You will see several predicted hurricane paths, each presented as a black dot. These dots show the probable path of the storm center. Hazardous conditions can occur outside of these paths.*” None of the text was italicized in the experiment.

For each trial, participants viewed a map of the United States Gulf coastline with a predicted hurricane path displayed as either the cone of uncertainty or a distribution of zoomies (see Figure 1). Participants responded to the question “Should the town be evacuated?” by clicking ‘Yes’ or ‘No’. The visualization was displayed until they indicated their response; there was no time limit. No feedback was provided.

Participants completed one block for the cone of uncertainty and one block for the zoomies. The block order was counterbalanced across participants, and trial order was randomized within each block. Each block contained 144 trials for a total of 288 trials.

RESULTS

Mean evacuation rates as a function of town position, participant group, and visualization condition are shown in Figure 2. Responses were analyzed to assess two aspects of behavior: decision transitions and decision thresholds. Both are described below. Data scripts available at <https://osf.io/rxhsv/>.

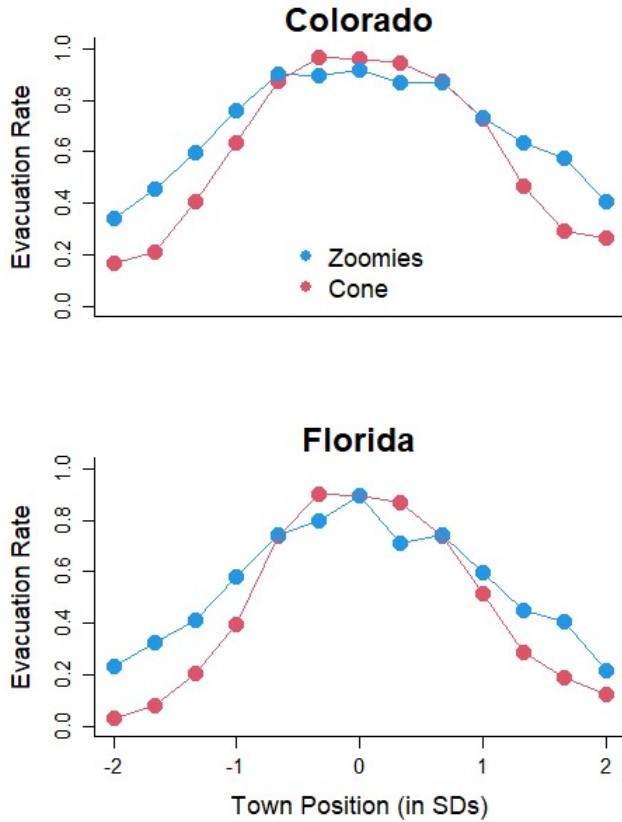


Figure 2. Mean evacuation rates for participants attending school in Colorado versus Florida as a function of town position and visualization condition.

Decision Transitions

Decision transitions refer to how decisions transitioned from being more likely to evacuate to being less likely to evacuate. In the case of abrupt transitions, the shift occurs swiftly over a short distance. For example, the containment effect is the idea that all towns located within the cone will be evacuated and towns located outside of the cone are perceived to not be at risk and are therefore not evacuated. The containment effect would lead to an abrupt transition. In contrast, if risk is perceived to gradually decrease with towns located further from the center of the storm's predicted path, the transition should be gradual or less abrupt. Decision transitions were calculated as half the distance required to shift responses from 75% evacuation rates to 25% evacuation rates.

Decision transitions (and 95% confidence intervals based on bootstrapping methods) are shown in Figure 3. Smaller decision transitions indicate a more abrupt shift from deciding to evacuate to deciding not to evacuate. In other words, for smaller decision transitions, the distance across which responses shift is shorter. Decision transitions were more abrupt (smaller) for the cone condition than for the zoomies condition. Participants had a greater sense of the risk for towns located beyond the boundaries of the cone in the zoomies condition. Decision transitions were similar across the two participant groups.

Being a student in Florida did not measurably impact decision transitions for either visualization compared with students in Colorado. Using the bootstrap method, we calculated the 95% CIs for the difference between the two participant groups. These intervals overlapped zero for both the cone $[-0.03, 0.04]$ and the zoomies $[-0.11, 0.04]$.

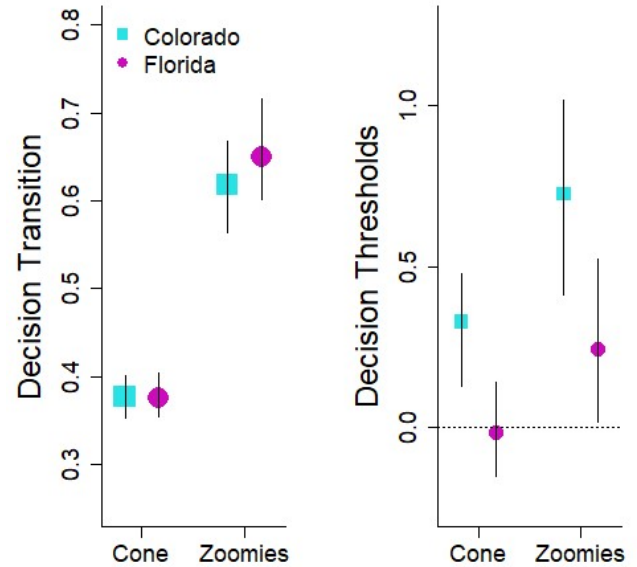


Figure 3. Decision Transitions (left) and Decision Thresholds (right) as a function of visualization condition and participant group. Both are in units of storm SDs. Error bars are 95% confidence intervals via the bootstrap method. Left: Smaller decision transitions signify a more abrupt transition from being more likely to evacuate to being less likely to evacuate. Right: Decision thresholds at zero indicate the threshold was at 1 SD (which also coincides with the edge of the cone). Positive values indicate thresholds at locations beyond 1 SD; negative values indicate threshold at locations closer than 1 SD.

Decision Thresholds

Another aspect of behavior is the decision threshold. The *decision threshold* refers to the distance from the center of the predicted storm path where decisions are to evacuate 50% of the time. Towns located within this threshold will be more likely to be evacuated and towns located outside this threshold will be less likely to be evacuated. Decision thresholds were calculated as the distance at which evacuation rates were 50%.

Decision thresholds are shown in Figure 3. Decision thresholds are the distance at which evacuation rates are at 50%. Thresholds at 0 indicate the threshold is located at 1 SDs, which is the same location as the edge of the cone. Positive values indicate decision thresholds beyond 1 SD, and negative values indicate decision thresholds less than 1 SD. Decision thresholds were further away from the center of the storm's predicted path in the zoomies condition than in the cone condition. We calculated the 95% CIs for the difference between the decision thresholds for the zoomies versus the cone condition. These

intervals did not include zero for the Colorado participants [0.26, 0.55] nor for the Florida participants [0.12, 0.37].

Decision thresholds were also further away for the Colorado participants than for the Florida participants. The 95% CIs for the difference between the decision thresholds for the Colorado participants versus the Florida participants was positive and did not include zero for the cone [0.14, 0.51] nor for the zoomies [0.15, 0.78]. For the Florida participants, their thresholds were right at the edge of the cone for the cone of uncertainty condition. This is consistent with the containment effect, where towns located inside of the cone are evacuated and towns outside of the cone are not evacuated.

Prediction Uncertainty

We recalculated decision transitions and decision thresholds at each level of prediction uncertainty for each participant group for each visualization condition. The corresponding scores are shown in Figures 4 and 5. For storms with low uncertainty, decision transitions were less abrupt and decision thresholds were further from the storm's center compared with storms with high uncertainty for both visualization conditions and participant groups. In cases with low uncertainty presented via zoomies, participants evacuated towns at the edge of the distribution of zoomies. Because we had not included towns far beyond this distribution, estimates of both decision transitions and decision thresholds were less precise (as indicated by the larger confidence intervals). Future studies should use a wider distribution of town locations.

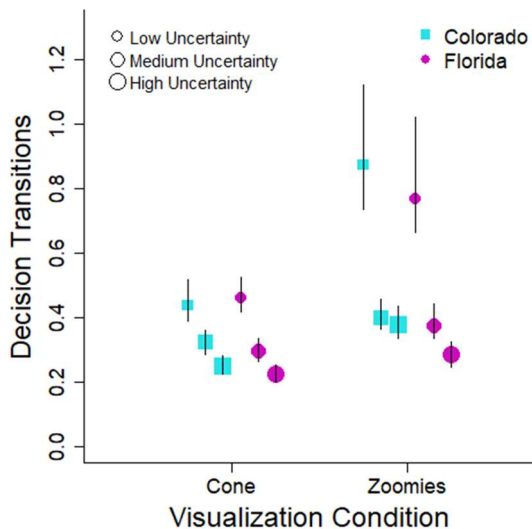


Figure 4. Decision Transitions (in units of storm SDs) as a function of visualization condition, participant group, and storm uncertainty. Error bars are 95% confidence intervals via the bootstrap method.

In general, decision transitions and decision thresholds were similarly affected by prediction uncertainty across the two participant groups. However, for the participants in Florida, the decision threshold was always at the edge of the cone for the

cone condition regardless of storm uncertainty. Hence familiarity with the cone visualizations was associated with a tendency to make standard judgments relative to the cone rather than extracting different information from different widths of cones.

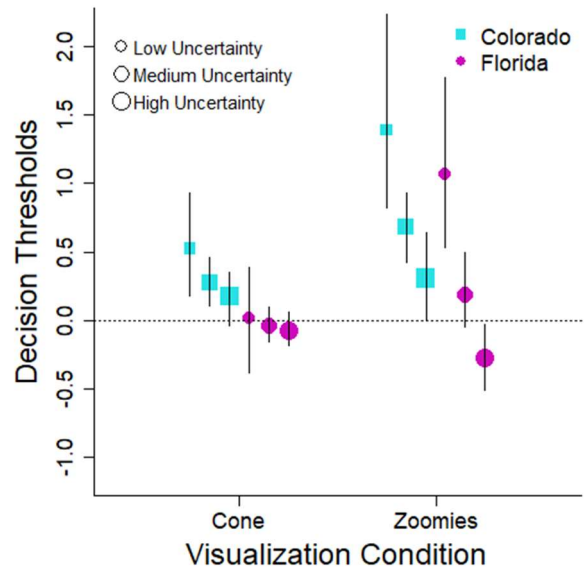


Figure 5. Decision Thresholds (in units of storm SD) as a function of visualization condition, participant group, and storm uncertainty. Decision thresholds at zero indicate the threshold was at 1 SD (which also coincides with the edge of the cone). Error bars are 95% confidence intervals via bootstrapping.

DISCUSSION

Hurricanes wreak havoc on coastal communities, with loss of lives, homes, businesses, and millions of dollars. Minimizing these costs requires effective communication of predictions of incoming storms. Yet, these predictions are inherently uncertain. Given that the mind struggles to understand uncertainty and reason under conditions with uncertainty, the task of communicating hurricane predictions is crucial and challenging.

A common technique for communicating hurricane predictions is the cone of uncertainty, despite the variety of issues raised with this visualization strategy (see Introduction). One issue is the containment effect, such that people perceive that only areas encompassed by the cone are at risk.

Evidence for the containment effect was found here, particularly for participants who attended university in West Florida. For these participants, the threshold at which their responses shifted from being more likely to evacuate to be less likely to evacuate coincided with the edge of the cone. Furthermore, their responses transitioned abruptly, with 78% of towns located within the cone to be evacuated and 79% of towns located beyond the cone to not be evacuated. A similarly abrupt transition was also evident in the students attending university in Colorado (see Figures 2 and 3).

These data show that direct experience with hurricane uncertainty does not necessarily provide an advantage in evaluating risk. One possible explanation for the more

conservative approach to evacuations in the Florida sample could be more experiences with false alarms in storm warnings and evacuations. Because evacuations are very time consuming, orders are typically made well in advance of landfall when uncertainty is high. This means that evacuation orders lead to false alarms as much as 90% of the time (Regnier, 2008). Additionally, the decision to evacuate is influenced by many factors (e.g., Morss et al., 2016), such as perceptions of warnings being overblown and anticipated traffic delays. A more experienced sample would be more likely to consider some of these barriers to evacuations. This may shift the criterion for those in hurricane prone areas to only recommend evacuation when a city is well within the cone of uncertainty, thereby showing a stronger containment effect.

In contrast, the zoomies depicted some level of risk across the distribution of the potential path, particularly at the edges of the storm's predicted path. Participants did not demonstrate a containment effect with the zoomies. Instead, their evacuation rates showed a gradual decrease as town distance increased. This behavior is more consistent with the actual risk of impending storms given the best predictions currently offered.

Given that participants from Florida were likely more accustomed to seeing and using the cone of uncertainty to make decisions, we can assess whether this familiarity impacted their interpretation of the zoomies. Evacuation rates were similar between the two groups on the zoomies. This suggests that transitioning from using the cone of uncertainty to using the zoomies will not incur a cost for people who are more accustomed to seeing and using the cone of uncertainty.

The zoomies are a dynamic ensemble. Perception of the zoomies likely benefits from the visual system's immense capability to process properties of ensembles of objects (Whitney & Yamanashi Leib, 2018). Other ensemble displays include track ensembles for which potential hurricane paths are represented as lines or tracks. Prior work has shown similar evacuation decisions for static track ensembles as for the zoomies (Witt & Clegg, 2021). However, a potential advantage for zoomies is that they have a natural compatibility between the visual display and the underlying concept. The zoomies can travel along similar paths as hurricanes.

The spread of the zoomies can indicate uncertainty about the storm's path, thus avoiding the common error with the cone of uncertainty that increased cone size is misinterpreted as a prediction of increased storm size instead of increased uncertainty with time.

Another advantage of the zoomies is that they can easily be manipulated to show a variety of features, such as using size or color to indicate various components of the impending threat such as storm surge or windspeed. In addition, the timing of the zoomies could provide a useful technique for communicating earliest reasonable as well as likely landfall of the impending hurricane. Future studies will be needed to determine whether people are sensitive to these features and can use them to make evacuation decisions. Given the variety of these potential visual manipulations, we propose zoomies will be able to convey impending hurricane information more precisely and therefore lead to smarter evacuation decisions.

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