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Perceptions and reactions to tornado warning polygons: Would a gradient polygon be useful?

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ABSTRACT

To better understand people's interpretations of National Weather Service's tornado warning polygons, 145 participants were shown 22 hypothetical scenarios in one of four displays—deterministic polygon, deterministic polygon + radar image, gradient polygon, and gradient polygon + radar image. Participants judged each polygon's numerical strike probability (p_s) and reported the likelihood of taking seven different response actions. The deterministic polygon display produced p_s that were highest at the polygon's centroid and declined in all directions from there. The deterministic polygon + radar display, the gradient polygon display, and the gradient polygon + radar display produced p_s that were high at the polygon's centroid and also at its edge nearest the tornadic storm cell. Overall, p_s values were negatively related to resuming normal activities, but positively correlated with expectations of resuming normal activities, seeking information from social sources, seeking shelter, and evacuating by car. These results replicate the finding that participants make more appropriate p_s judgments when polygons are presented in their natural context of radar images than when the polygons are presented in isolation and that gradient displays appear to provide no appreciable benefit. The fact that p_s judgments had moderately positive correlations with both sheltering (a generally appropriate response) and evacuation (a generally inappropriate response) provides experimental confirmation that people threatened by actual tornadoes are conflicted about which protective action to take.

1. Introduction

Recent studies have concluded that the National Weather Service's (NWS's) advances in disseminating warnings have succeeded in reducing tornado casualties [1–3]. In one recent effort, the NWS replaced county-wide tornado warnings with smaller warning polygons that more specifically identify the risk area. Disseminating warning polygons in lieu of county-based warnings reduces the number of people that are warned unnecessarily, thus reducing social disruption and economic losses as well as avoiding a potential reduction in source credibility that might be caused by numerous false alarms [4]. However, the conventional deterministic warning polygon has only a single boundary line that identifies the area in which people should take protective action; people outside the polygon are advised to simply monitor the news media or resume normal activities. Recent research suggests that people's interpretation and response to these polygons may be inconsistent with the NWS's expectations [5–10]. These results call for further research to better understand how recipients perceive and react to tornado polygons. The purpose of this paper, therefore, is to address this deficiency by examining the effects of different types of tornado polygons on people's risk perceptions and expected immediate responses to tornado threat.

2. Literature review

The theoretical basis of this study is the *Protective Action Decision Model* [11–13], which summarizes the findings of more than six decades of research on people's response to warnings about environmental hazards [14–18]. According to the PADM, people's protective action decisions begin with social warnings, social cues, and environmental cues. These information sources, together with personal characteristics such as past experience, produce changes in people's situational perceptions and, ultimately, behaviors such as information search and protective response. In particular, the PADM predicts that different types of graphical displays contained in warning messages from social sources will affect people's interpretation of the risk information, as indicated by their judgments that they will be struck by an environmental hazard (i.e., their threat perceptions). In turn, these strike

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probability (p_s) judgments will affect their expectations of taking different types of behavioral responses such as information seeking and protective action.

One limitation of research on warnings in the disaster research literature on which the PADM is based has been a focus on the verbal and numeric content of warnings. Specifically, warning messages have been found to be most likely to produce appropriate protective actions if they describe the information source, threat, its location and arrival time, affected (and safe) areas, especially vulnerable populations, protective action recommendations, and sources to contact for additional information and assistance [12,19,20]. Other message characteristics include perceived source credibility, message consistency, message accuracy, message clarity, perceived confidence and certainty, guidance clarity, and message frequency [21,22] and comprehension agreement, dose-response consistency, hazard-response consistency, uniformity, audience evaluation, and types of communication failures [23]. Only recently has it been recognized that messages can include graphic, as well as verbal and numeric information, in warnings about hurricanes [24–28]. However, there has been a more active line of research on tornado warning polygons, as reviewed in the next section.

2.1. Empirical studies on tornado polygons

Experiments on tornado polygons have specifically addressed two issues. First, what is the perceived risk at different locations inside and outside the polygon? Second, how do alternative information displays affect those risk perceptions? Concerning the first question, past experiments have consistently found a strong *centroid effect*; people judge the highest p_s to be at the polygon's centroid when they are shown a deterministic polygon in isolation [5,7,8,29]. This is inconsistent with NWS guidance, which implies that all locations within the polygon are equally likely to be struck.

Another important response to deterministic polygons is a weak *edge effect* associated with a polygon's boundary. This edge effect refers to the extent to which participants use a polygon's edges as a threshold of appraising their risk. NWS guidance specifically states that people need not take protective actions outside the warning polygon, indicating that the risk there is negligible. Accordingly, if people follow this guideline, their p_s judgments outside the polygon should be substantially lower than those inside the polygon. In contrast to this strong edge effect, recent studies found only weak edge effects, as indicated by participants' p_s judgments being only slightly lower just outside its edges than just inside those edges [5,7,8].

On the second question, how do alternative polygon displays affect participants' p_s judgments, Klockow [30] randomly assigned participants to the cells of a 2 (verbal probability label—"high" vs. "low") by 6 (polygon type) experimental design. There were two deterministic polygons—a "short warning" that included only the two closest test locations and a "long warning" that included all four test locations. The four probabilistic displays varied in their color schemes—a red gradient polygon, a spectral polygon, a divergent polygon (p_s ranged from dark orange—the highest value—through light orange, white, and light blue to dark blue), and an unshaded contour polygon. All polygons produced similar results, especially the colored probabilistic displays.

Ash et al. [5] compared the conventional deterministic polygon display that has a single boundary with two types of probabilistic polygon displays—a spectral polygon and a gradient polygon. Unlike the deterministic polygon, which does not differentiate areas of varying risk within its boundaries, the spectral display divided the polygon into nine regions that were color coded—the highest risk area being dark red and the lowest risk area being light blue. The gradient display divided the polygon into five regions that differentiated the risk within a polygon, but using different shades of a single color (red); the highest risk area was filled in dark red and the remaining risk areas were filled with increasingly lighter shades of red. Ash et al. [5] found that the probabilistic polygons (spectral or gradient) produced weaker centroid and edge effects than the conventional (deterministic) polygon.

Casteel and Downing [31] added texts and radar images to warning polygons, presenting 24 scenarios in one of four formats—text only, text + warning polygon, text + radar image, and text + warning polygon + radar image—on a simulated smart phone screen. The text message described a tornado warning for the respondent's area, the warning expiration time, and a shelter recommendation. The results showed that the addition of a radar image and warning polygon to text information produced no increase in participants' ratings of perceived severity, risk, or likelihood of contacting loved ones.

Jon et al. [7], on the other hand, coupled a deterministic polygon with radar images of storm cells on which the polygon was based. In their study, participants viewed three different displays: a polygon-only display, a polygon + tornado storm cell display, and a polygon + multiple storm cells display. Their results were similar to Ash et al. [5] in finding a weaker centroid effect for the two radar displays than for the polygon-only display; in both radar displays, p_s judgments were as high at the edge nearest the storm cells as at the centroid.

Miran et al. [32] examined four different types of polygons. Similar to Ash et al. [5], they presented participants a red gradient polygon and a four-color (red, orange, yellow, green) spectral polygon, but also added a gray gradient polygon and an unshaded contour polygon. Each polygon was presented with and without a radar image of the generating storm and each colored display was accompanied by a legend that indicated the p_s range for each of the colors (the unshaded polygons had numerical values displayed within each contour). Analysis of participants' p_s accuracy scores revealed that displays without radar images were more accurate and there were no significant differences among the display types without radar images, although participants strongly preferred the spectral display.

In summary, existing research has shown that a probabilistic polygon-only display is superior to conventional deterministic polygon-only display in producing increases in p_s judgments at the near edge of the polygon and, thus, producing expected protective actions that are more consistent with NWS guidance. This result provides some insight into people's cognitive processing of polygon displays by suggesting that few, if any, participants viewing deterministic polygon-only displays realized that the narrow edge of the polygon was the one nearest the tornadic storm cell—despite the fact that a sophisticated viewer could infer this from simple statistical reasoning (uncertainty is lowest, and therefore the polygon's edge is narrowest, at the beginning of a forecast interval). Indeed, even an explicit statement about the storm's direction has been insufficient for experiment participants to infer the location of the storm cell [7,8].

2.2. Implications of tornado polygon research findings

Research on tornado polygons has yielded five important findings. First, there is a *display effect* arising from significant differences in responses to different types of polygon displays, with a probabilistic polygon-only display and a deterministic polygon + radar display both being superior to a deterministic polygon-only display. These results raise a question whether a probabilistic polygon display, with or without a radar display, would produce p_s judgments at the near edge of the polygon that are any better than a deterministic polygon + radar display. As a theoretical issue, the question is whether a probabilistic polygon provides the same threat information as a deterministic polygon + radar display. As a practical matter, the question is whether the NWS should superimpose a probabilistic polygon rather than a deterministic polygon onto its radar displays.

Second, there is a *centroid effect;* in the absence of information about the location of a tornadic storm cell, people appear to interpret a deterministic polygon as a contour line of constant probability with the location of highest risk at the centroid [5,7,8,29]. This centroid effect is consistent with findings from other studies that people use a *proximity heuristic* that generates a perceived risk gradient in which perceived risk