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Perceptions and Reactions to Tornado Warning Polygons: Would a Gradient Polygon Be Useful?

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Perceptions and Reactions to Tornado Warning Polygons: Would a Gradient Polygon Be Useful?

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.

Keywords: Tornado warning polygons; risk perceptions; protective actions

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 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 [5,29,7,8]. 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 decreases with distance from the expected impact location [33,8,27,34]. Consequently, a proximity effect would cause the centroid effect to diminish, if not disappear, when information about the location of a tornadic storm cell outside the polygon is available.

Third, there is a weak *edge effect*; previous tornado polygon studies have reported that p_s judgments are lower just outside than just inside the polygon [5], but the decrease is a continuous function rather than the NWS's intended threshold function (i.e., a *strong edge effect*—[8,7]). This weak edge effect can be interpreted as a special case of a more general *transect effect*, in which a tornado's strike probability decreases with increasing distance perpendicular to the storm cell's apparent track. In the case of the many trapezoidal tornado polygons, observers should be able to infer the storm cell's track from the longitudinal axis so a transect effect will be revealed decreases in p_s judgments along the polygon's lateral transects.

Fourth, people's risk judgments and emotional reactions based on tornado polygon displays are consistent with their expected response actions [5,7,8]. The link between p_s judgments and expected response actions is a crucial element in the policy implications that can be drawn from tornado polygon studies. Only if p_s judgments are related to protective actions do these studies have implications for tornado warnings. Of course, behavioral expectations are not necessarily the same as actual behavior but hurricane evacuation expectations have been found to be significantly correlated with people's actual evacuation behavior two years later [35]. Moreover, a recent statistical meta-analysis found that the results from studies of people's responses to hypothetical hurricane scenarios have been quite similar to those from studies of people's responses to actual hurricanes [15]. Thus, it is important to continue examining people's responses to hypothetical tornado scenarios.

Fifth, tornado polygon research has examined whether people's personal characteristics affect their risk perception and expected responses to tornado polygons. The broader literature on warning response has examined the relationship of risk perception with variables such as gender [36-38] and hazard experience [39-41]. These tornado polygon studies have reported that females are less likely to ignore warnings and more likely to take protective actions, as well as that those with previous polygon experience are less likely to ignore warnings [7,8].

2.3 Research Hypotheses and Research Questions

The research literature summarized in the previous sections yields six research hypotheses about p_s judgments at different points around a tornado polygon, one research hypothesis about the correlations of p_s judgments with expected response actions, and one research question about the relative preference for sheltering and evacuation at different locations within the polygon. In addition to testing whether there are differences among the four types of displays, this section examines whether it is possible to replicate the results from previous tornado polygon studies. Replication is important because recent publications have emphasized the prevalence of spurious findings in behavioral research and the need for replications to confirm that reported effects are reliable [42-44].

The first hypothesis examines previous findings of a display effect by predicting that the three displays providing information about the location of the tornadic storm cell will be similar to each other but different from a deterministic polygon-only display.

RH1: There will be nonsignificant differences in the patterns of p_s judgments among the deterministic polygon + radar display, gradient polygon-only display, and gradient polygon + radar displays, but all three will be significantly different from the deterministic polygon-only display.

The first part of the next hypothesis tests whether the centroid effect found in previous studies will be replicated in a deterministic polygon-only display [5,7,8,29] whereas the second part of the hypothesis seeks to confirm the reduction of the centroid effect in a deterministic polygon + radar display [7]. In addition, the second part of the hypothesis tests whether the gradient polygon-only and gradient polygon + radar displays, which also indicate the location of the storm cell, also reduce the centroid effect. The centroid effect can be assessed by evaluating p_s judgments along the four lateral transects defined in Figure 1. Transect 1 (T1) is perpendicular to the polygon centerline and just inside the polygon's front (narrow) edge nearest to the storm cell, T2 is also perpendicular to the polygon centerline and passes through the polygon's centroid, T3 is just inside the polygon's back (wide) edge, and T4 is just outside the polygon's back edge.

RH2a: Participants' p_s judgments at the polygon centroid will be significantly different from the grid cells inside the polygon on transect T1 for the deterministic polygon-only display (Grid cell E2 >

D1, E1, F1—see Figure 1 for these locations) but not for a deterministic polygon + radar display or either gradient display (E2 = D1, E1, F1).

RH2b: Participants' p_s judgments at the polygon centroid will be significantly different from the grid cells inside the polygon on transects T2 and T3 for the deterministic polygon-only display but not for a deterministic polygon + radar display or either gradient display (E2 > D1, E1, F1, C2, G2, B3, E3, H3).

The third hypothesis examines whether the deterministic polygon + radar display and both gradient displays produce a proximity effect, in which p_s judgments decrease with distance from the tornadic storm cell for successive grid cells along the centerline.

RH3: The deterministic polygon + radar display and both gradient displays will exhibit a proximity effect in which p_s judgments decline along the centerline with increasing distance from the centroid (E2 > E3, E3 > E4).

The fourth hypothesis addresses the replicability of the weak edge effect, as opposed to the strong edge effect implied by NWS guidance [5,7,8].

RH4: In all four displays, p_s judgments will be greater for the grid cells just inside the polygon's lateral edges than for the grid cells just outside its lateral edges on transects T1, T2, and T3 (D1 > C1; C2 > B2; B3 >A3; F1 > G1; G2 > H2; H3 > I3).

The fifth hypothesis tests the presence of the transect effect, in which p_s judgments will be greater for the grid cells closer to the centerline than for those farther from it.

RH5a: The deterministic polygon + radar display and both gradient displays will exhibit a transect effect *inside* the polygon, in which p_s judgments decline with distance from the centerline along on transects T1, T2, and T3 (E1 > D1, E1 > F1, E2 > C2, E2 > G2, E3 > B3, E3 > H3).

RH5b: All four displays will exhibit a transect effect *outside* the polygon's lateral edges, in which p_s judgments will be greater for the grid cells just outside the polygon's lateral edges than for those grid cells on the same transect that are farther from the centerline on transects T1 and T2 (C1 > B1; B2 > A2; G1 > H1; H2 > I2).

RH5c: In all four displays, p_s judgments beyond the polygon on transect T4 will be greater for the grid cell at the centerline than for the grid cells that are farther from the centerline (E4 > A4; E4 > I4).

The sixth hypothesis tests the impact of combinations of effects. Specifically, RH6a tests the combination of proximity and transect effects *inside* the polygon, RH6b tests the combination of proximity and transect effects *outside* the polygon, and RH6c tests the combination of proximity, transect, and edge effects.

RH6a: In all four displays, p_s judgments will be greater for the grid cells *inside* the polygon that are closer to the storm cell and the centerline than for the grid cells that are farther from the storm cell and the centerline (D1 > C2; C2 > B3; F1 > G2; G2 > H3).

RH6b: In all four displays, p_s judgments will be greater for the grid cells *outside* the polygon that are closer to the storm cell and the centerline than for the grid cells that are farther from the storm cell and the centerline (C1 > B2; B2 > A3; B1 > A2; G1 > H2; H2 > I3; H1 > I2).

RH6c: In all four displays, p_s judgments will be greater for the grid cells just inside the polygon that are closer to the storm cell and the centerline than for the grid cells that are just outside the polygon and farther from the storm cell and the centerline (B3 > A4; H3 > I4).

The last research hypothesis tests whether results this study can replicate the results from previous tornado polygon studies regarding the correlates of p_s judgments and expected response actions.

RH7: Female gender and White ethnicity; prior experience with radar and polygon displays, tornado warnings, and tornado damage; expected personal consequences of a tornado strike; and tornado p_s judgments will be negatively correlated with resuming normal activities but positively correlated with expectations of information seeking and protective action.

Previous studies have reported that sheltering and evacuation were positively correlated ($r = .30$ [8]; $r = .18$ [7]) and that p_s judgments had stronger correlations with sheltering ($r = .68$ [8]; $r = .50$ [7]) than with evacuation ($r = .23$ [8]; $r = .38$ [7]). However, it is unclear if there were differences in the patterns of sheltering and evacuation expectations at different points in the warning polygon. Ideally, the grid cells nearest the storm cell should indicate greater expectations of sheltering because there would not be enough time to evacuate before a tornado struck.

RQ1: Are shelter expectations greater than evacuation expectations on all three transects inside the polygon?

3. Research Methods

3.1 Design

This experiment has one between-subjects factor (display type: deterministic polygon only, deterministic polygon + radar display, gradient polygon only, and gradient polygon + radar display) and one within-subjects factor (22 points inside and outside the polygon arranged as described in Figure 1).

3.2 Participants

Data were collected from volunteers recruited through the University of Washington student newspaper in January 2017; each was paid $25. There were 146 volunteers who registered, but only 145 participated. Overall, the sample was predominantly female (68%) and single (98%), with an average age of 22.8. They were most likely to identify themselves as Asian or Pacific Islanders (59.2%), following by Caucasians (33.1%), African Americans (3.5%), Hispanics (2.8%), and Native Americans (0.7%). Only a minority had previously seen a tornado polygon (17%). Among those who had experienced tornado warnings (32%), 49% had taken a protective action at least once, whereas 51% of them had ignored a warning at least once. Very few participants had previous tornado damage experience (0.07 on a scale 0-7).

3.3 Procedure

Participants began by reading the NWS's brief descriptions of deterministic warning polygons and radar images (in the relevant conditions) as the experimenter read them aloud. This material was originally found at www.srh.noaa.gov/images/bmx/aware/swaw_2010/web_version_pages_p6.pdf but is reproduced in Appendix A. The experimenter told them to imagine being on a road trip in which they checked into a motel in Des Moines Iowa in the late afternoon. While unpacking, a TV newscaster reported that a line of thunderstorms was moving northeast at 20 mph and the NWS had issued a tornado warning. Each tornado scenario displayed the motel location designated by a blue dot and a tornado polygon defined by a red isosceles trapezoid that was the same size and orientation in all 22 scenarios. For example, Figure 1 displays the scenario in which the blue dot was located at H2. To provide participants with a consistent frame of reference, the blue dot representing the motel location was always located at the center of the screen and the location of the polygon varied.

The deterministic polygon-only display showed the blue dot and a polygon with a single boundary that divided the warned area from the unwarned area (see Figure 2a). The deterministic polygon + radar display supplemented the deterministic polygon with a simulated radar image showing a storm cell with a hook echo and two flanking non-tornadic storm cells (see Figure 2b). The gradient polygon-only display showed the blue dot and five overlapping polygons that divided the warned area into areas of varying risk and separated it from the unwarned area (see Figure 2c). The gradient polygon + radar display supplemented the gradient polygon with the same radar display as in the deterministic polygon + radar image display (see Figure 2d). Each participant viewed all 22 tornado scenarios but viewed only one type of display (i.e., display was a between-subjects manipulation). As shown in Figure 2, each warning polygon's far edge (the one farthest from the storm front) was longer than its near edge, indicating increasing uncertainty about the strike location with distance from the storm cell. The radar display of the tornadic storm cell had colors ranging from blue through green, yellow, and orange to red. Furthermore, as described to the participants, the tornadic storm cell had a hook echo indicating a circular wind rotation that signals tornado formation. The participants were not informed about the tornado's intensity.

After viewing each scenario, participants judged the likelihood of the tornado striking them (5-point scale ranging *Extremely unlikely* = 1 to *Extremely likely* = 5) and then used this scale to rate their likelihood of taking each of seven different response actions. According to the NWS, the most appropriate response for those inside the polygon, but not those outside it, is to seek shelter in an interior room or hallway. It is less appropriate for those inside the polygon to take other common response actions such as seeking additional information by watching the weather forecast on TV, trying to get more information from other people (in this case, the motel desk clerk), or trying to get more information on the Internet. All of these actions delay implementation of the appropriate response. The least appropriate responses for those inside the polygon have also been found to be common during tornadoes—ignore the weather forecast and continue what they were doing, go outside to see if a tornado is coming, or get into a car and drive someplace safer. There was no constraint on the amount of time the participants could take to complete their responses to each hypothetical tornado.

After responding to all 22 tornado scenarios, participants answered four sets of questions measuring their expected personal consequences of a tornado strike. Participants used a 5-point scale to rate the likelihood that, if the tornado struck the motel, their room would be severely damaged or destroyed, their car would be severely damaged or destroyed, their luggage would be severely damaged or destroyed, and they would be severely injured or killed. In addition, they reported previous tornado warning experience in terms of having seen a warning polygon on TV (*No* = 0, *Yes* = 1), having taken protective action after receiving a tornado warning and (*No* = 0, *Yes* = 1), and having taken *no* protective action after receiving a tornado warning (*No* = 0, *Yes* = 1). Participants reported previous tornado impact experience with tornado property damage in their city (*No* = 0, *Yes* = 1), damage to their home (*No* = 0, *Yes* = 1), damage to the home of a friend, relative, neighbor, or coworker they know personally (*No* = 0, *Yes* = 1), injury to themselves or members of their immediate family (*No* = 0, *Yes* = 1), injury to a friend, relative, neighbor, or coworker they know personally (*No* = 0, *Yes* = 1), disruption to their school that prevented them from attending (*No* = 0, *Yes* = 1), and disruption to their shopping and other daily activities (No = 0, Yes = 1). These seven items were summed to produce a measure of previous tornado damage experience, which resulted in a scale with $\alpha = .79$. Finally, participants were also asked to report their age (*Under 21* = 1, *21-25* = 2, *26-30* = 3, *31-35* = 4, and *Over 35* = 5), gender (*Male* = 0, *Female* = 1), ethnicity (*African American* = 1, *Asian or other Pacific Islander* = 2, *Caucasian* =3, *Hispanic* = 4, and *Native American* = 5), marital status (*Married* =1, *Single* = 2, *Divorced*= 3, and *Widowed* = 4), education level (*Some high school* = 1, *High school graduate/GED* = 2, *Some college/vocational school* = 3, *College graduate* = 4, *Graduate school* = 5), income level (*Less than $25,000* = 1, *$25,000–49,999* = 2, *$50,000–74,999* = 3, *$75,000–99,999* = 4, *$100,000 or more* = 5), and homeownership (*Rent* = 0, *Own* = 1).

4. Results

4.1. Preliminary Test

Overall, 93.8% (136/145) of participants completed all questionnaire items. The highest missing data rate ranged between 2.9%-5.9%, which yielded a nonsignificant result for Little's [45] MCAR (missing completely at random) test in all four conditions (χ^2 values ranged 0-13.9, all $p = 1.00$). Because it is fair to assume the missing values are completely at random, the Expectation-Maximization algorithm in SPSS 17.0 was used to estimate the missing values. Given the large number of comparisons among grid cells required to test the research hypotheses, $p < .01$ was used as the statistical significance level.

4.2 Data Processing

This experiment yielded four sets of mean p_s judgments for each of the 22 tornado scenarios—one set of means for each of the four display conditions. Figure 3 displays these mean p_s judgments in a 4 rows by 9 columns matrix indicating the motel's location in relation to the polygon for each tornado scenario. The red cells indicate the scenarios in which the motel was inside the polygon and the gray cells indicate the locations scenarios in which the motel was outside the polygon. To test RH1, participant's p_s judgments were transformed to accuracy scores in the following manner. For cells inside the polygon, participants' p_s ratings were subtracted from 5 (indicating the participant's deviation from the NWS assessment that these cells have the highest possible strike probability). For cells outside the polygon, the participants' p_s ratings had 1 subtracted from the participant's p_s rating (indicating the participant's deviation from the NWS assessment that these cells have the lowest possible strike probability). Thus, smaller scores indicate greater accuracy (i.e., consistency with NWS guidance). The differences among the display conditions were assessed using a One Way Analysis of Variance (ANOVA) on participants' mean (over the 22 tornado scenarios) accuracy scores.

To test RH2-RH6, the differences in mean p_s judgments between locations were assessed using MANOVA followed by *t*-tests. To test RH7, the mean p_s judgment and mean likelihood rating for each expected immediate response were calculated over the 22 scenarios and used to calculate the correlations among demographic characteristics, experience variables, p_s judgments, and expected response actions ratings. To address RQ1, the differences between mean shelter and evacuation expectations at selected locations were assessed using *t*-tests.

4.2. Test Results for Research Hypotheses and Question

Partly consistent with RH1 (There will be nonsignificant difference in the patterns of p_s judgments among the deterministic polygon + radar, gradient polygon-only, and gradient polygon + radar displays, all of which will be significantly different from the deterministic polygon-only display), a MANOVA revealed significant effects for display (Wilks' $\Lambda = 0.25$, $F_{66,359} = 3.27$, $p < .001$), and intercept (Wilks $\Lambda = 0.02$, $F_{22,120} = 346.13$, $p < .001$). The posttest ANOVA on the mean accuracy scores yielded a significant effect ($F_{3,141} = 4.03$, $p < .001$). As expected, the gradient polygon-only display ($M = 1.11$) and gradient polygon + radar display ($M = 1.15$) had smaller accuracy scores than the deterministic polygon-only display ($M = 1.29$). Unexpectedly, however, the deterministic polygon + radar display ($M = 1.26$) had accuracy scores that were virtually indistinguishable from the deterministic polygon-only display. Only the difference between the gradient polygon-only display and the deterministic polygon-only display was statistically significant ($p = .02$) and even this difference was less than 4% of the range of the 5-point rating scale.

Partly consistent with RH2a (Participants' p_s judgments at the polygon centroid will be significantly different from the grid cells inside the polygon on transect T1 for the deterministic polygon-only display but not for a deterministic polygon + radar display or either gradient display), *t*-tests revealed that—as hypothesized—the polygon centroid (E2) in the deterministic polygon-only display had significantly higher p_s judgments than the three grid cells within the polygon on T1 (D1, E1, and F1), see Table 1, Rows 1-3. The mean differences ranged from 0.91 (23% of the scale range) to 1.03 (26% of the scale range). In addition, *t*-test results for the deterministic polygon + radar display indicated that—as hypothesized—the polygon centroid (E2) had nonsignificant differences of 1-7% of the scale range from the three grid cells within the polygon on T1. However, contrary to hypothesis, there was a different pattern of results for the two gradient displays. In the gradient polygon-only display, the centroid had significantly higher p_s judgments than grid cell D1 and in the gradient polygon + radar display, the centroid had significantly higher p_s judgments than grid cells D1 and F1.

Partly consistent with RH2b (Participants' p_s judgments at the polygon centroid will be significantly different from the grid cells inside the polygon on transects T2 and T3 for the deterministic polygon-only display but not for a deterministic polygon + radar display or either gradient display), p_s judgments at the polygon centroid were significantly different from the grid cells inside the polygon on transects T2 and T3 for the deterministic polygon-only display (Rows 4-8). The mean differences in the four display conditions were relatively large, ranging from 23-39% of the response scale. In addition, there were nonsignificant differences among the eight grid cells just inside the polygon's lateral edges (D1, E1, F1, C2, G2, B3, E3, and H3) in all four display conditions. However, contrary to hypothesis, this pattern also was found in the deterministic polygon + radar display and both gradient displays.

Mostly consistent with RH3 (The deterministic polygon + radar display and both gradient displays will exhibit a proximity effect in which p_s judgments decline along the centerline with increasing distance from the centroid), both comparisons (E2 > E3 and E3 > E4) were statistically significant in five of the six comparisons, see Rows 9-11. Unexpectedly, however, the difference between the centroid (E2) and the centerline grid cell inside the polygon (E3) was generally larger than the difference between the centerline grid cell inside the polygon (E3) and the one outside the polygon (E4). The mean differences in the four display conditions were relatively small, ranging from 8-19% of the response scale.

Consistent with RH4 (In all four displays, p_s judgments will be greater for the grid cells just inside the polygon's lateral edges than for the grid cells just outside its lateral edges on Transects 1, 2, and 3), Table 1, Rows 12-17 reveal that all grid cells inside the polygon's lateral edges on each transect (grid cells D1 and F1 on T1, C2 and G2 on T2, and B3 and H3 on T3) were significantly greater than their adjacent grid cells just outside the polygon's lateral edges (C1 and G1 on T1, B2 and H2 on T2, A3 and I3 on T3). The mean differences for Rows 12-17 varied from 20-44% of the scale range.

Mostly consistent with RH5a (The deterministic polygon + radar display and both gradient displays will exhibit a transect effect inside the polygon, in which p_s judgments decline with distance from the centerline along each transect), p_s judgments generally declined with distance from the centerline along T2 and T3. However, T1 elicited two nonsignificant differences (E1 ≈ D1, F1) in the deterministic polygon + radar display (0-18% of the response scale, Rows 18-19). Although all four displays produced consistently large differences on T2 (12-31% of the response scale, Rows 20-21), they produced nonsignificant differences on T3 (0-6% of the response scale, Rows 22-23).

Consistent with RH5b (All four displays will exhibit a transect effect *outside* the polygon's lateral edges, in which p_s judgments will be greater for the grid cells just outside the polygon's lateral edges than for those grid cells on the same transect that are farther from the centerline), Figure 3 shows that each of the two grid cells just outside the polygon's lateral edges on T1 and T2 (grid cells C1 and G1 on T1 and B2 and H2 on T2) was significantly greater than its adjacent grid cell farther outside the polygon's lateral edges (B1 and H1 on T1, A2 and I2 on T2). The mean differences for Rows 24-27 were consistently large—ranging from 17-30% of the scale range.

Partially consistent with RH5c (In all four displays, p_s judgments beyond the polygon on Transect 4 will be greater for the grid cell at the centerline than for the grid cells that are farther from the centerline), Figure 3 shows that grid cell E4 received higher p_s judgments than both A4 and I4 in the deterministic polygon + radar display and both gradient displays. Rows 28-29 show that all of the differences were statistically significant but moderately large, with the exception of the difference between E4 and I4 in the deterministic polygon-only display. The mean differences ranged from 11-22% of the response scale.

Partially consistent with RH6a (In all four displays, p_s judgments will be greater for the grid cells *inside* the polygon that are closer to the storm cell and the centerline than for the grid cells that are farther from the storm cell and the centerline), Rows 30-33 show that p_s judgments generally declined with a combination of distance from the tornadic storm cell and the polygon centerline inside the polygon in the deterministic polygon + radar, gradient polygon-only, and gradient polygon + radar displays—all of which indicated the location of the tornadic storm cell (mean differences ranging from 15-17% of the response scale). By contrast, all of the relevant comparisons were nonsignificant in the deterministic polygon-only display (mean difference of 0% of the response scale).

Mostly contrary to RH6b (In all four displays, p_s judgments will be greater for the grid cells *outside* the polygon that are closer to the storm cell and the centerline than for the grid cells that are farther from the storm cell and the centerline), Rows 34-39 show there were generally nonsignificant differences in p_s judgments for all of the relevant comparisons. The significant differences that did occur were inconsistent across display conditions and the mean differences ranged from 1-12% of the response scale).

Consistent with RH6c (In all four displays, p_s judgments will be greater for the grid cells just inside the polygon that are closer to the storm cell and the centerline than for the grid cells that are just outside the polygon and farther from the storm cell and the centerline), Rows 40-41 show that p_s judgments declined significantly when the proximity effect and transect effect combined with an edge effect, with mean differences ranging from 26-33% of the response scale).

Partially consistent with RH7 (Female gender and White ethnicity; prior experience with radar and polygon displays, tornado warnings, and tornado damage; expected personal consequences of a tornado strike; and tornado p_s judgments will be negatively correlated with resuming normal activities but positively correlated with expectations of information seeking and protective action), Table 2 indicates the demographic variables had only two significant correlations out of 14—female participants were less likely to seek environmental cues (r = -.27), whereas Whites were less likely to ignore the threat (r = -.16). Moreover, none of the 48 correlations of the experiential variables with p_s judgments and expected response actions was statistically significant. However, two of the eight correlations of expected personal consequences with p_s judgments and expected response actions were significant (information outside and evacuate) and six of the seven correlations of p_s judgments with expected response actions were significant (all except seeking environmental cues outside).

In response to RQ1 (Are shelter expectations greater than evacuation expectations on all the transects inside the polygon), Table 3 reveals some very weak results—only three of 36 (=8%) of the differences were significant and the mean differences only ranged from -.03 to +.12. First, the deterministic polygon-only display produced significantly more sheltering than evacuation at the polygon centroid, a pattern that was repeated in the gradient polygon + radar display but not the other two displays. In addition, the gradient polygon + radar display produced greater expectations of sheltering than evacuating at only one of the grid cells inside the polygon on transect T1.

5. Discussion

The fundamental objective of this study was to compare the effects of a deterministic polygon (with and without a radar display) and a gradient polygon (also with and without a radar display) on p_s judgments and expected response actions. The effectiveness of these tornado risk communication displays can be gauged by observing the extent to which participants' p_s judgments expected response actions are consistent with the NWS's recommended behavioral responses inside and outside the polygon. This discussion, therefore, addresses five aspects of the study. The first aspect is the display effect—whether there are differences among the displays and whether the displays that indicate the location of the tornadic storm cell are superior to the deterministic polygon-only display. The second aspect is the centroid effect—people's tendency to judge the polygon centroid as the location of highest risk, and how that changes with different types of displays. As noted below, the centroid effect generalizes to a proximity effect in which p_s judgments decline with increasing distance from the tornadic storm cell rather than distance from the polygon centroid.

The third aspect is the edge effect, in which p_s judgments decrease immediately outside the polygon's boundaries—either slightly in the weak edge effect or substantially in the strong edge effect. The edge effect generalizes to a transect effect, in which p_s judgments decline continuously with increasing distance from the polygon's longitudinal axis rather than discretely across the polygon's edges. The discussion of the centroid and edge effects addresses growing concerns about the replicability of behavioral research [42-44] by assessing whether the results of previous tornado polygon studies are confirmed. Finally, the fourth aspect concerns the degree to which demographic and experiential variables are related to p_s judgments and expected response actions.

5.1 Display effect

The weak partial confirmation of RH1 (There will be nonsignificant difference in the patterns of p_s judgments among the deterministic polygon + radar display, gradient polygon-only, and gradient polygon + radar displays, all of which will be significantly different from the deterministic polygon-only display) suggests that two methods of providing information about the location of the tornadic storm cell—the radar display and the gradient polygon—are essentially intersubstitutable. That is, one is equivalent to the other and a combination of the two is no better than either one alone.

This finding is generally consistent with previous research on tornado warning polygons. Klockow's [30] comparison of deterministic polygons with probabilistic polygons (displays that varied in their color schemes) found no significant differences. Similarly, Casteel and Downing's [31] combination of text and radar images showed that the additional information did not produce statistically significant enhancement of the warning effectiveness. Although Ash et al. [5] reported a significant difference between the p_s judgments of deterministic polygons and probabilistic polygons (gradient polygons using different colors or different shades of a single color) that produced weaker centroid and edge effects as compared to a deterministic polygon, they did not provide a condition that displayed radar images. Consequently, it is difficult to compare their results with those that did use radar images in the warning polygon displays [7,30]. The fact that another study reported better accuracy for displays that lacked radar images [32] suggests that these display effects are small and inconsistent, so it makes little difference what type of polygon the NWS superimposes onto radar displays.

5.2 Centroid effect

The results from RH2a (Participants' p_s judgments at the polygon centroid will be significantly different from the grid cells inside the polygon on transect T1 for the deterministic polygon-only display but not for a deterministic polygon + radar display or either gradient display) confirmed people's tendency to perceive higher risk at the polygon's centroid than at its near edge. This effect was consistently strong (mean differences from 23-26% of the range in the 1-5 response scale) in the deterministic polygon-only display where no contextual information was given about the location of the tornadic storm cell. The results for this condition are consistent with those of previous studies of polygon-only displays [5, 7, 8, 29].

Moreover, the test of RH2b (Participants' p_s judgments at the polygon centroid will be significantly different from the grid cells inside the polygon on transects T2 and T3 for the deterministic polygon-only display but not for a deterministic polygon + radar display or either gradient display) indicated that providing a radar display reduced the centroid effect but did not eliminate it. That is, interior grid cells on T1 (D1, E1, F1) elicited p_s judgments that were just as high as the centroid rather than higher than the centroid. These results confirm previous findings that, when provided with information about the location of a tornadic storm cell by a radar image, people recognize that there is a *great* threat at the near edge of the polygon [7]. Unfortunately, they fail to recognize that there is a *greater* threat there than at the centroid.

5.3 Proximity effect

The results from RH3 (The deterministic polygon + radar display and both gradient displays will exhibit a proximity effect in which p_s judgments decline along the centerline with increasing distance from the centroid) supported the proximity effect but showed that the E3-E4 difference was slightly larger than the E2-E3 difference in the deterministic polygon-only condition but the reverse was true (and much stronger) in the other conditions. This result is surprising because the E2-E3 difference is only a proximity effect whereas the E3-E4 difference is both a proximity effect and an edge effect. This finding replicates previous results [7] and suggests that information about the location of the tornadic storm cell accentuates the perceived distance of the polygon's far edge from its centroid.

5.4 Edge effect

The results from RH4 (In all four displays, p_s judgments will be greater for the grid cells just inside the polygon's lateral edges than for the grid cells just outside its lateral edges on Transects 1, 2, and 3) are consistent with previous findings that grid cells just outside the polygon had significantly lower mean ratings than their adjacent grid cells just inside the polygon, a pattern that was generally consistent across the four displays [5,7,8]. However, the edge effect was much weaker than the threshold effect that would be consistent with the NWS's recommendations because the mean p_s judgment (2.55) was substantially larger than the minimum rating (1.00). Indeed, even the mean p_s judgment (1.76) for the grid cells that were farther away from the polygon edge (A2, B1, I2, and H1) was notably larger than the minimum rating—which raises the question how far away must the polygon edge be from the respondent's location before the p_s is assumed to be negligible.

5.5 Transect effect

The results of RH5a (The deterministic polygon + radar display and both gradient displays will exhibit a transect effect *inside* the polygon, in which p_s judgments decline with distance from the centerline along each transect) consistently supported the hypothesis on T2 (the transect through the centroid), consistently contradicted the hypothesis on T3, and were inconsistent on T1. Curiously, the patterns of results for the two deterministic polygon displays were identical to each other and the patterns of results for the two gradient polygon displays were also identical to each other. The most likely explanation for this difference is that the lines in the gradient display accentuated the differences in risk between the grid cell on the centerline (E1) and the two adjacent cells (D1 and F1). It is less obvious why all four displays yielded transect effects on T2 but not on T3, which replicates a previously reported pattern [7]. One possible explanation for the nonsignificant differences on T3 is that the proximity effect produced a decline in p_s judgments from T2 to T3 that overwhelmed the decline due to the gradient effect from E3 to B3 and H3. Of course, this explanation is speculative and needs to be tested in future studies.

The results of RH5b (All four displays will exhibit a transect effect *outside* the polygon's lateral edges, in which p_s judgments will be greater for the grid cells just outside the polygon's lateral edges than for those grid cells on the same transect that are farther from the centerline) are also consistent with previous findings in that the mean p_s judgments decrease with distance from the polygon's perimeter [7, 8]. These results suggest that the edge effect is just a special case of the more general transect effect that is entirely consistent with other research that has shown evidence of evacuation shadow in response to a variety of hazards [11-13]. The practical implication of this finding is that, contrary to the NWS's recommendations, people are likely to take protective actions in areas well beyond the tornado polygon edges.

The results for RH5c (In all four displays, p_s judgments beyond the polygon on Transect 4 will be greater for the grid cell at the centerline than for the grid cells that are farther from the centerline) indicate that all three alternatives to the deterministic polygon-only display elicited transect effects but this result raises two questions. First, why was the transect effect weaker in the deterministic polygon-only display than in the other displays and, second, why did the other displays produce transect effects on T4 but not on T3? Further research is needed to determine if these disparities can be replicated and explained.

The results for RH6a (In all four displays, p_s judgments will be greater for the grid cells *inside* the polygon that are closer to the storm cell and the centerline than for the grid cells that are farther from the storm cell and the centerline) provide further support for both the proximity effect and the transect effect, although the relative contribution of these two effects to these results cannot be determined. One important implication of this finding is that there is likely to be incomplete compliance with the NWS protective action recommendation (i.e., immediate shelter) in many parts of the tornado polygon.

The results for RH6b (In all four displays, p_s judgments will be greater for the grid cells *outside* the polygon that are closer to the storm cell and the centerline than for the grid cells that are farther from the storm cell and the centerline) indicate no support for the hypothesis. In general, the comparisons of the relevant grid cells were nonsignificant. This result indicates that, although the proximity effect produced declining p_s judgments with distance from the storm cell and the transect effect produced declining p_s judgments with distance from the centerline, the combination of these two effects was, essentially, zero. One explanation for this result is that observers were able to make reliable comparisons between grid cells along one dimension (either proximity to the storm cell or proximity to the centerline) but had insufficient cognitive capacity to produce consistent p_s judgments for comparisons involving two dimensions. Alternatively, a more likely explanation is that these grid cells form a contour of constant p_s judgments that parallels the polygon edge. This is further evidence that identifying the location of the storm cell only reduces, rather than eliminates, the negative effect of people's pre-existing beliefs about the interpretation of the polygon edges as equivalent to a topographical contour that has the centroid as the location of maximum p_s.

The results for RH6c (In all four displays, p_s judgments will be greater for the grid cells just inside the polygon that are closer to the storm cell and the centerline than for the grid cells that are just outside the polygon and farther from the storm cell and the centerline) were strongly supportive of the hypothesis in all four displays. In comparison with the results for RH6b, the results for this hypothesis suggest that the polygon edge was a much stronger cue for p_s judgments than the combination of a proximity effect and transect effect.

5.6 Effects of displays on shelter and evacuation expectations

The results for RQ1 (Are shelter expectations greater than evacuation expectations on all the transects inside the polygon) indicate that the participants had no general tendency to prefer one of the protective actions anywhere inside the polygon, regardless of the type of display they viewed. This result is rather puzzling because the p_s judgments seem to indicate that the deterministic polygon + radar and the two gradient displays are effective in identifying the close proximity of the storm cell to transect T1. Thus, they should indicate a greater need to shelter promptly rather than evacuate for those grid cells. One possible explanation for these results is that the participants in this study had generally low levels of experience with tornadoes, so they failed to realize the implication of their p_s judgments for the choice of protective action. Further research is needed to determine if people that have more experience with tornado warnings consider proximity to a tornadic cell when deciding whether to shelter or evacuate.

5.7 Correlates of p_s judgments and expected response actions

Regarding RH7 (Female gender and White ethnicity; prior experience with radar and polygon displays, tornado warnings, and tornado damage; expected personal consequences of a tornado strike; and tornado p_s judgments will be negatively correlated with resuming normal activities but positively correlated with expectations of information seeking and protective action), Table 2 shows that the only 3 percent (2/64) of the correlations of demographic and experiential variables with p_s judgments were statistically significant. This finding is consistent with some previous results [8], which found only 7 percent (4/54) of those correlations were significant, although somewhat less consistent with other previous results [7], which found 21 percent (10/48) of those correlations were significant. It is notable that none of the correlations that were significant in one of the three studies were also significant in either of the other two studies. This finding is consistent with studies concluding that demographic and experiential variables are inconsistent predictors of hurricane evacuation [15,46].

On the other hand, p_s judgments were significantly correlated with six of the seven expected response actions. Thus, this study's results are consistent with previous findings in revealing that p_s judgments were negatively correlated with resuming normal activities and positively correlated with information seeking, sheltering, and evacuating [7,8]. This is an important finding because it means that the findings regarding the centroid, proximity, edge, and transect effects—along with differences among the polygon displays—have significant implications for people's responses to NWS tornado warnings.

5.8 Study limitations

All studies have their limitations and this one is no exception. The participants were mostly students who were from a region that is notable for the rarity of tornadoes. Although most participants (74%) had seen a radar display, only a minority (17%) had ever seen a tornado polygon. Moreover, the participants responded to hypothetical scenarios, which might produce somewhat different responses than actual situations. However, this sample produced results in the polygon-only condition that were similar to those in a sample with a significantly higher level of tornado experience [8]. Moreover, a recent review of hurricane evacuation research reported that studies of hypothetical hurricanes and surveys of responses to actual hurricanes produced similar results [15]. Another study limitation is that the scenarios were not randomized across participants. Moreover, because the scenarios were only presented in one order, it is not possible to assess the magnitude of any order effects such as the one reported in [8]. Nonetheless, although the two different orders in that study produced different mean ratings in each of the cells, they did not change the fundamental patterns of effects. Specifically, they both produced a centroid effect and an edge effect. A final limitation of the present study is that all polygons were isosceles trapezoids that provided advance warning of the arrival of the tornadic storm cell. Although an Internet search indicates that this appears to be the most common type of tornado polygon, there are other quadrilaterals as well as polygons with five or more sides—some of which are superimposed over the storm cell. Future research should also examine p_s judgments and expected response actions to these other types of polygons.

6. Conclusions

Although NWS guidance implies that p_s judgments should be uniformly high within the polygon and uniformly low outside it, this is not the case. Participants' p_s judgments are indeed higher inside than outside the polygon but they vary systematically within each of these two locations. First, as was the case in previous studies, a deterministic polygon-only display elicits higher p_s judgments at the centroid than in grid cells just inside the polygon's perimeter [5,7,8,29]. The most concerning aspect of this centroid effect is that it understates the risk at grid cells inside the polygon's front edge on transect T1. Second, as in [7], addition of a radar display to the deterministic polygon reduced, but did not eliminate, the centroid effect. That is, the grid cells inside the polygon on transect T1 received p_s judgments that are just as high as, rather than significantly lower than, those at the centroid.

Overall, the data suggest that observers interpret a polygon's perimeter as a contour of constant p_s and that they tend to use this perimeter together with an assumed risk gradient to infer higher p_s values in concentric rings inside the polygon and lower p_s values in concentric rings outside it. This inferential process is most clearly revealed in the deterministic polygon-only display where p_s judgments are high at the centroid, significantly lower in the ring of grid cells just inside the perimeter (which have roughly equal p_s judgments), significantly lower still in the ring of grid cells just outside the perimeter (which also have roughly equal p_s judgments), and lowest in the ring of grid cells beyond that (which also have roughly equal p_s judgments). Even when they see the deterministic NWS display, which implies $p_s = 1$ inside the polygon and $p_s = 0$ outside it, observers infer a continuous an underlying continuous probability function. Providing a display that identifies the location of the storm cell modifies the perceived probability function by increasing p_s judgments on transect T1 inside the near edge and decreasing them on transect T3 inside the far edge. The fact that providing information about the location of the tornadic storm cell only reduces the centroid effect rather than eliminates it suggests that it is difficult for observers to suppress an assumption that the polygon is a contour line of equal probability that surrounds a peak probability at the centroid.

These findings are theoretically important because the identification of centroid, proximity, edge, and transect effects adds to the development of design principles for graphical warning displays just as research regarding effects of variables such as information source; threat type, impact location, and arrival time; affected (and safe) areas; especially vulnerable populations; protective action recommendations; and sources to contact for additional information and assistance has added to the development of design principles for verbal and numeric warning displays. The findings of this study are also important because p_s judgments are correlated with both shelter and evacuation expectations, indicating that people are likely to act on these risk judgments—as predicted by the PADM [11-13]. In addition, shelter and evacuation expectations are correlated with each other, reproducing a finding from field studies that people do, indeed, take both of these protective actions [47-49]. Also, the significant correlations of p_s judgments with protective action expectations, coupled with the finding of significant differences in p_s judgments *inside* the polygon, indicates that there is a potential for under-response to the NWS's protective action recommendation. Moreover, the finding of significant differences in p_s judgments *outside* the polygon suggests that there is a potential for over-response to the NWS's protective action recommendation. This finding is quite similar to results from studies of hurricane evacuation studies that also find under-response in areas warned to evacuate and over-response in nearby areas that are told it is safe to remain in their homes [50].

Examination of the effects of the four displays on p_s judgments revealed little or no differences. This finding has theoretical significance because it suggests that superimposing a deterministic polygon over a radar image provides observers the same information about the area that is at greatest risk as substituting a gradient polygon for the deterministic polygon. Three displays—deterministic polygon + radar, gradient polygon-only, and gradient polygon + radar—are equivalent in their ability to identify the polygon edge nearest the storm cell as a location at great risk. This finding has practical significance because NWS tornado warnings routinely superimpose the deterministic polygon over radar images. Thus, there appears to be no reason for the NWS to substitute gradient polygons for the current deterministic polygons. Nonetheless, it is important to recognize that the three alternatives to the deterministic polygon-only display only *reduced* the centroid effect; none of them *eliminated* it. Consequently, an important direction for future research will be to identify ways to eliminate the centroid effect altogether.

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Table 1: Statistical Test Results for RH2-6.

Comparison	Condition A: Deterministic polygon only		Condition B: Deterministic polygon + radar display		Condition C: Gradient polygon only		Condition D: Gradient polygon + radar display	
	Difference	Test result	Difference	Test result	Difference	Test result	Difference	Test result
RH2a: Centroid effect								
1. E2 > D1	0.91	$t_{33} = 6.41$, $p < .001$	-0.03	$t_{34} = -0.24$, *ns*	0.40	$t_{34} = 3.64$, $p < .01$	0.63	$t_{40} = 6.14$, $p < .001$
2. E2 > E1	0.91	$t_{33} = 5.51$, $p < .001$	0.29	$t_{34} = 1.66$, *ns*	-0.09	$t_{34} = -0.90$, *ns*	-0.07	$t_{40} = -0.68$, *ns*
3. E2 > F1	1.03	$t_{33} = 6.41$, $p < .001$	-0.09	$t_{34} = -0.59$, *ns*	0.14	$t_{34} = 1.54$, *ns*	0.41	$t_{40} = 4.20$, $p < .001$
MD*	0.95		-0.06		0.16		0.33	
RH2b: Centroid effect								
4. E2 > C2	1.00	$t_{33} = 7.49$, $p < .001$	0.89	$t_{34} = 6.58$, $p < .001$	1.06	$t_{34} = 8.18$, $p < .001$	1.22	$t_{40} = 11.97$, $p < .001$
5. E2 > G2	0.74	$t_{33} = 7.56$, $p < .001$	0.49	$t_{34} = 3.68$, $p < .01$	0.74	$t_{34} = 5.93$, $p < .001$	0.93	$t_{40} = 8.23$, $p < .001$
6. E2 > B3	0.97	$t_{33} = 7.89$, $p < .001$	1.06	$t_{34} = 7.80$, $p < .001$	1.60	$t_{34} = 10.01$, $p < .001$	1.83	$t_{40} = 15.86$, $p < .001$
7. E2 > E3	0.76	$t_{33} = 5.71$, $p < .001$	1.06	$t_{34} =6.46$, $p < .001$	1.54	$t_{34} = 9.61$, $p < .001$	1.83	$t_{40} = 13.57$, $p < .001$
8. E2 > H3	1.00	$t_{33} = 7.14$, $p < .001$	1.14	$t_{34} = 8.00$, $p < .001$	1.63	$t_{34} = 10.98$, $p < .001$	1.88	$t_{40} = 18.79$, $p < .001$
MD*	0.90		0.93		1.32		1.54	
RH3: Proximity effect								
9. E1 > E2	-0.91	$t_{33} = 5.51$, $p < .001$	-0.29	$t_{34} = 1.66$, *ns*	0.09	$t_{34} = -0.90$, *ns*	0.07	$t_{40} = -0.68$, *ns*
10. E2 > E3	0.76	$t_{33} = 5.71$, $p < .001$	1.06	$t_{34} = 6.46$, $p < .001$	1.54	$t_{34} = 9.61$, $p < .001$	1.83	$t_{40} = 13.57$, $p < .001$
11. E3 > E4	1.03	$t_{33} = 6.01$, $p < .001$	0.51	$t_{34} = 3.01$, $p < .01$	0.66	$t_{34} = 3.78$, $p < .01$	0.17	$t_{40} = 1.04$, *ns*
MD*	0.30		0.43		0.76		0.69	
RH4: Edge effect								
12. D1 > C1	1.21	$t_{33} = 8.70$, $p < .001$	1.71	$t_{34} = 11.79$, $p < .001$	1.74	$t_{34} = 13.22$, $p < .001$	1.68	$t_{40} = 11.54$, $p < .001$
13. F1 > G1	0.94	$t_{33} = 7.07$, $p < .001$	0.86	$t_{34} = 7.33$, $p < .001$	1.57	$t_{34} = 10.52$, $p < .001$	1.24	$t_{40} = 9.27$, $p < .001$
14. C2 > B2	0.91	$t_{33} = 5.70$, $p < .001$	1.09	$t_{34} = 6.55$, $p < .001$	1.09	$t_{34} = 9.15$, $p < .001$	1.00	$t_{40} = 7.39$, $p < .001$

15. G2 > H2	1.21	$t_{33} = 7.43, p < .001$	1.40	$t_{34} = 8.23, p < .001$	1.46	$t_{34} = 7.88, p < .001$	1.61	$t_{40} = 10.09, p < .001$
16. B3 > A3	1.00	$t_{33} = 7.14, p < .001$	1.26	$t_{34} = 9.11, p < .001$	0.97	$t_{34} = 5.67, p < .001$	1.05	$t_{40} = 6.72, p < .001$
17. H3 > I3	1.00	$t_{33} = 7.49, p < .001$	0.80	$t_{34} = 6.58, p < .001$	0.80	$t_{34} = 5.68, p < .001$	0.71	$t_{40} = 6.04, p < .001$
MD*	1.04		1.18		1.27		1.22	
RH5a: Transect effect/inside								
18. E1 > D1	0.00	$t_{33} = 0.00$, *ns*	-0.31	$t_{34} = 2.07$, *ns*	0.49	$t_{34} = 4.36, p < .001$	0.71	$t_{40} = 5.03, p < .001$
19. E1 > F1	0.12	$t_{33} = 0.85$, *ns*	-0.37	$t_{34} = 2.19$, *ns*	0.23	$t_{34} = 2.76, p < .01$	0.49	$t_{40} = 3.38, p < .01$
20. E2 > C2	1.00	$t_{33} = 7.49, p < .001$	0.89	$t_{34} = 6.58, p < .001$	1.06	$t_{34} = 8.18, p < .001$	1.22	$t_{40} = 11.97, p < .001$
21. E2 > G2	0.74	$t_{33} = 7.56, p < .001$	0.49	$t_{34} = 3.68, p < .01$	0.74	$t_{34} = 5.93, p < .001$	0.93	$t_{40} = 8.23, p < .001$
22. E3 > B3	0.21	$t_{33} = 1.75$, *ns*	0.00	$t_{34} = 0.00$, *ns*	0.06	$t_{34} = 0.37$, *ns*	0.00	$t_{40} = 0.00$, *ns*
23. E3 > H3	0.24	$t_{33} = 1.76$, *ns*	0.09	$t_{34} = 0.46$, *ns*	0.09	$t_{34} = 0.50$, *ns*	0.05	$t_{40} = 0.37$, *ns*
MD*	0.38		0.13		0.44		0.57	
RH5b: Transect effect/outside								
24. C1 > B1	0.65	$t_{33} = 4.45, p < .001$	0.69	$t_{34} = 3.97, p < .001$	0.91	$t_{34} = 5.88, p < .001$	0.68	$t_{40} = 4.68, p < .001$
25. G1 > H1	1.03	$t_{33} = 7.19, p < .001$	1.20	$t_{34} = 7.61, p < .001$	1.20	$t_{34} = 5.55, p < .001$	1.37	$t_{40} = 10.55, p < .001$
26. B2 > A2	0.94	$t_{33} = 7.91, p < .001$	0.80	$t_{34} = 6.23, p < .001$	0.91	$t_{34} = 5.20, p < .001$	1.10	$t_{40} = 10.04, p < .001$
27. H2 > I2	0.85	$t_{33} = 6.35, p < .001$	0.69	$t_{34} = 4.51, p < .001$	0.94	$t_{34} = 4.70, p < .001$	0.61	$t_{40} = 4.69, p < .001$
MD*	0.87		0.85		0.99		0.94	
RH5c: Transect effect/beyond the polygon								
28. E4 > A4	0.59	$t_{33} = 3.85, p < .01$	0.94	$t_{34} = 5.76, p < .001$	0.94	$t_{34} = 7.69, p < .001$	0.95	$t_{40} = 5.95, p < .001$
29. E4 > I4	0.29	$t_{33} = 1.89$, *ns*	0.74	$t_{34} = 4.63, p < .001$	0.49	$t_{34} = 3.51, p < .01$	0.78	$t_{40} = 4.42, p < .001$
MD*	0.44		0.84		0.72		0.87	
RH6a: Proximity/transect effect/inside								
30. D1 > C2	0.09	$t_{33} = 0.57$, *ns*	0.91	$t_{34} = 7.29, p < .001$	0.66	$t_{34} = 6.58, p < .001$	0.59	$t_{40} = 5.60, p < .001$

31. F1 > G2	-0.29	$t_{33} = 1.89$, *ns*	0.57	$t_{34} = 4.84$, $p < .001$	0.60	$t_{34} = 5.45$, $p < .001$	0.51	$t_{40} = 3.90$, $p < .001$
32. C2 > B3	-0.03	$t_{33} = 0.27$, *ns*	0.17	$t_{34} = 1.44$, *ns*	0.54	$t_{34} = 4.33$, $p < .001$	0.61	$t_{40} = 5.29$, $p < .001$
33. G2 > H3	0.26	$t_{33} = 2.18$, *ns*	0.66	$t_{34} = 4.64$, $p < .001$	0.89	$t_{34} = 6.05$, $p < .001$	0.95	$t_{40} = 7.57$, $p < .001$
MD*	0.01		0.58		0.67		0.66	
RH6b: Proximity/transect effect/outside								
34. C1 > B2	-0.21	$t_{33} = 1.49$, *ns*	0.29	$t_{34} = 1.97$, *ns*	0.00	$t_{34} = 0.00$, *ns*	-0.10	$t_{40} = 0.94$, *ns*
35. G1 > H2	-0.03	$t_{33} = 0.19$, *ns*	1.11	$t_{34} = 5.96$, $p < .001$	0.49	$t_{34} = 2.84$, $p < .01$	0.88	$t_{40} = 6.25$, $p < .001$
36. B2 > A3	0.06	$t_{33} = 0.42$, *ns*	0.34	$t_{34} = 2.65$, *ns*	0.43	$t_{34} = 2.77$, $p < .01$	0.66	$t_{40} = 4.63$, $p < .01$
37. H2 > I3	0.06	$t_{33} = 0.44$, *ns*	0.06	$t_{34} = 0.32$, *ns*	0.23	$t_{34} = 1.60$, *ns*	0.05	$t_{40} = 0.35$, *ns*
38. B1 > A2	0.09	$t_{33} = 0.83$, *ns*	0.40	$t_{34} = 2.42$, *ns*	0.00	$t_{34} = 0.00$, *ns*	0.32	$t_{40} = 2.81$, $p < .01$
39. H1 > I2	-0.21	$t_{33} = 2.03$, *ns*	0.60	$t_{34} = 2.98$, $p < .01$	0.23	$t_{34} = 1.16$, *ns*	0.12	$t_{40} = 0.96$, *ns*
MD*	-0.04		0.47		0.23		0.32	
RH6c: Proximity/transect/edge effect								
40. B3 > A4	1.41	$t_{33} = 9.61$, $p < .001$	1.46	$t_{34} = 8.53$, $p < .001$	1.54	$t_{34} = 10.30$, $p < .001$	1.12	$t_{40} = 7.75$, $p < .001$
41. H3 > I4	1.09	$t_{33} = 7.64$, $p < .001$	1.17	$t_{34} = 7.51$, $p < .001$	1.06	$t_{34} = 9.79$, $p < .001$	0.90	$t_{40} = 6.72$, $p < .001$
MD*	1.26		1.31		1.31		1.02	

*MD = Mean difference

Table 2. Means (*M*), Standard deviations (*SD*), and intercorrelations (r_{ij}) of variables pooled over four conditions.

Variable	M	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Female	.68	.47																
2. White	.33	.47	.02															
3. ExpRadar	.74	.52	.03	.26*														
4. ExpPolygon	.17	.37	.07	.24*	.29*													
5. ExpWrnAct	.18	.48	.01	.04	.40*	.07												
6. ExpWrnNo	.17	.37	.07	.08	.00	.15	.14											
7. ExpFalse	.21	.41	.14	.11	.09	.18	.41*	.55*										
8. ExpTorDam	.07	.15	.01	.05	.03	.16	.31*	.25*	.37*									
9. ExpPersCon	3.96	.86	-.13	-.11	-.04	-.12	.06	-.08	-.12	.09								
10. StrikeProb	2.89	.58	-.01	-.21	-.09	-.20	.10	-.13	-.01	-.04	.18							
11. Ignore	2.47	.78	-.02	-.26*	-.11	.00	-.21	.12	-.03	-.04	-.16	-.47*						
12. InfoOutside	2.64	1.05	-.27*	.13	.00	-.06	-.04	-.08	-.15	.11	.30*	.15	-.25*					
13. InfoTV	3.58	.78	.18	.07	.10	.07	.04	.02	.11	.01	.06	.29*	-.49*	.23*				
14. InfoInternet	3.71	.90	.07	-.09	.08	.06	.06	-.11	-.10	.02	.05	.27*	-.31*	.13	.45*			
15. InfoClerk	2.64	1.07	.13	-.15	-.06	-.12	-.02	-.11	-.13	-.03	.19	.43*	-.26*	.23*	.41*	.38*		
16. Shelter	2.44	.75	-.02	-.17	.06	-.12	.18	-.16	-.06	-.08	.01	.50*	-.34*	-.03	.16	.28*	.39*	
17. Evacuate	2.39	.86	-.14	-.16	-.19	-.12	-.11	-.08	-.15	-.08	.27*	.44*	-.27*	.35*	.05	.10	.30*	.23*

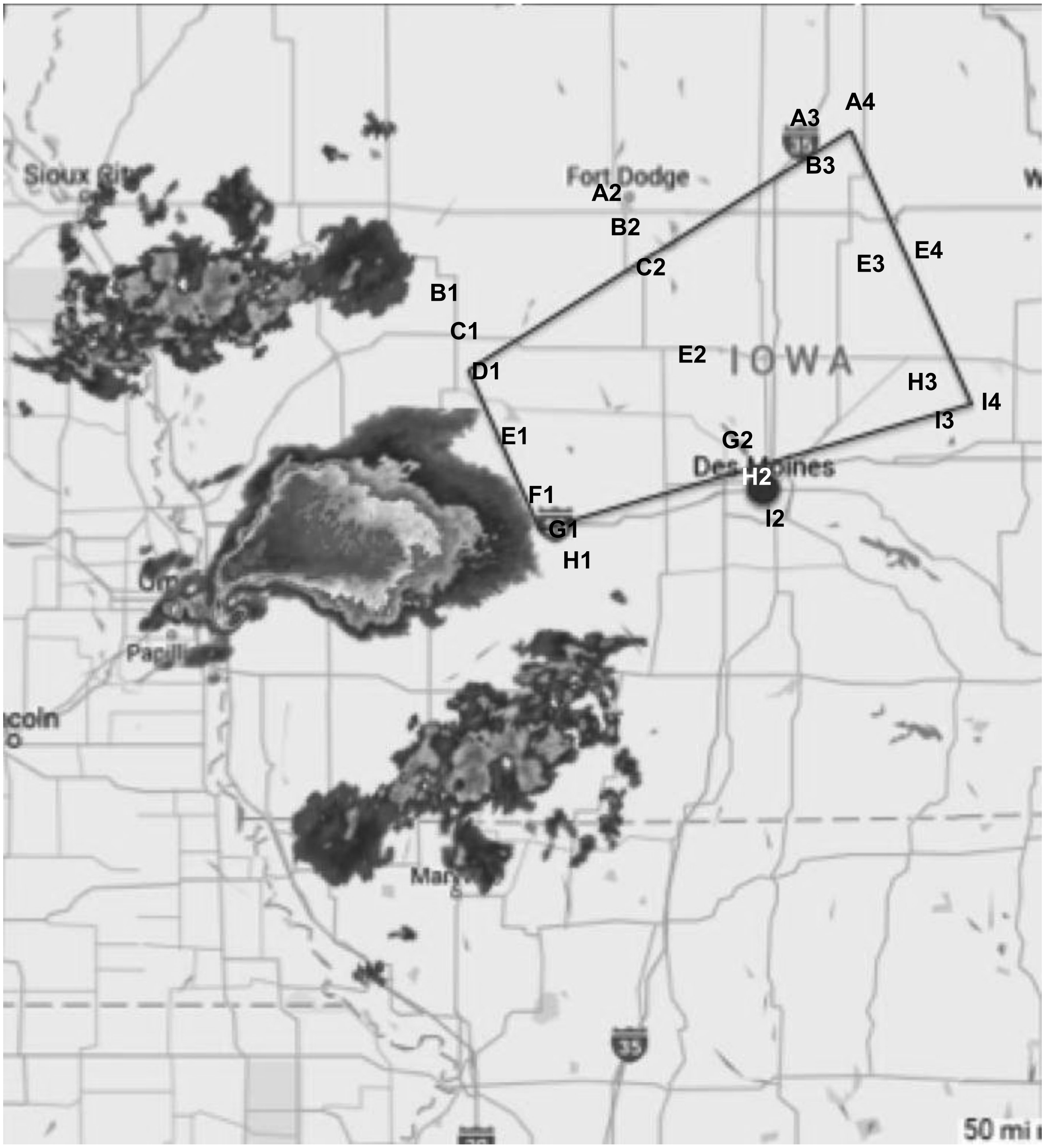
*Statistically significant at p < .01. 1. Female = respondent's gender; 2. White = respondent's ethnicity; 3. ExpRadar = previous experience seeing a radar display on TV; 4. ExpPolygon = previous experience seeing a tornado polygon on TV; 5. ExpWrnAct = previous experience receiving a tornado warning and taking protective action; 6. ExpWrnNo = previous experience receiving a tornado warning but not taking protective action; 7. ExpFalse = previous experience receiving a false alarm; 8. ExpTorDam = previous experience of tornado damages; 9. ExpPersCon = Expercted personal consequences of a tornado strike; 10. StrikeProb = p_s judgments; 11. Ignore = ignore the weather forecast and continue original works; 12. InfoTV = continue watching the weather forecast on TV; 13. InfoOutside = go outside to seek environmental cues; 14. InfoClerk = seeing information from the motel desk clerk; 15. InfoInternet = seeking information from the Internet; 16. Shelter = seeking a shelter; 18. Evacuate = getting into my car and evacuating.

Table 3. Differences in the expectation of taking response actions (shelter rating – evacuation rating).

Comparison	Condition A: Deterministic polygon only		Condition B: Deterministic polygon + radar display		Condition C: Gradient polygon only		Condition D: Gradient polygon + radar display	
	Difference	Test result	Difference	Test result	Difference	Test result	Difference	Test result
1. D1	-0.35	$t_{33} = 1.09$, *ns*	-0.26	$t_{34} = 0.65$, *ns*	0.43	$t_{34} = 1.20$, *ns*	0.54	$t_{40} = 1.58$, *ns*
2. E1	-0.24	$t_{33} = 0.77$, *ns*	0.23	$t_{34} = 0.60$, *ns*	0.14	$t_{34} = 0.31$, *ns*	1.02	$t_{40} = 2.34$, *ns*
3. F1	0.00	$t_{33} = 0.00$, *ns*	0.37	$t_{34} = 0.90$, *ns*	0.40	$t_{34} = 0.94$, *ns*	1.12	$t_{40} = 2.94$, $p < .01$
4. C2	-0.47	$t_{33} = 1.49$, *ns*	0.00	$t_{34} = 0.00$, *ns*	-0.34	$t_{34} = 1.01$, *ns*	0.32	$t_{40} = 1.11$, *ns*
5. E2	1.24	$t_{33} = 3.31$, $p < .01$	0.20	$t_{34} = 0.49$, *ns*	0.51	$t_{34} = 1.15$, *ns*	1.39	$t_{40} = 3.34$, $p < .01$
6. G2	0.09	$t_{33} = 0.28$, *ns*	-0.31	$t_{34} = 0.91$, *ns*	-0.27	$t_{34} = 0.80$, *ns*	0.56	$t_{40} = 2.07$, *ns*
7. B3	-0.24	$t_{33} = 0.80$, *ns*	-0.06	$t_{34} = 0.20$, *ns*	-0.17	$t_{34} = 0.59$, *ns*	0.12	$t_{40} = 0.60$, *ns*
8. E3	-0.35	$t_{33} = 0.97$, *ns*	-0.09	$t_{34} = 0.29$, *ns*	-0.34	$t_{34} = 1.26$, *ns*	0.10	$t_{40} = 0.43$, *ns*
9. H3	-0.65	$t_{33} = 1.83$, *ns*	-0.11	$t_{34} = 0.40$, *ns*	-0.26	$t_{34} = 1.03$, *ns*	0.31	$t_{40} = 1.55$, *ns*
MD*	-0.11		0.00		0.01		0.61	-0.11

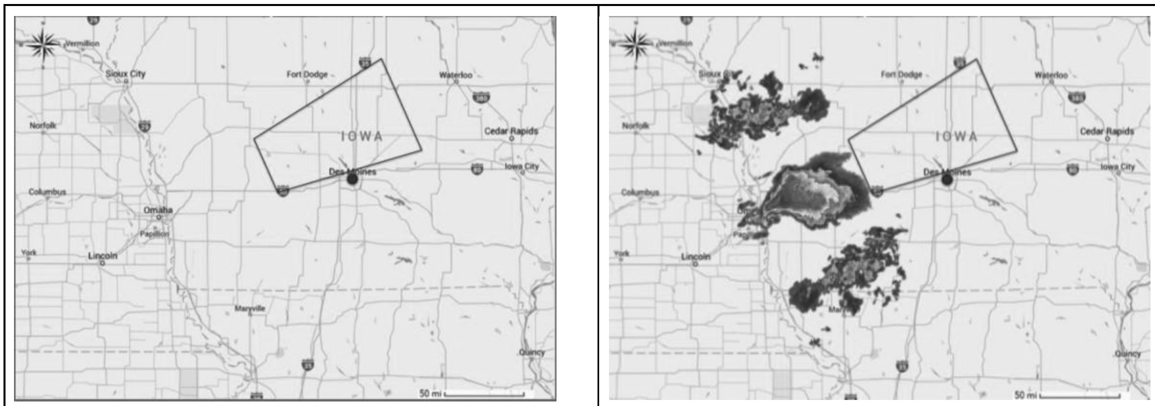
* Mean difference

Fig. 1 Storm Cells, Warning Polygon, and the Hypothesized Locations of the Motel



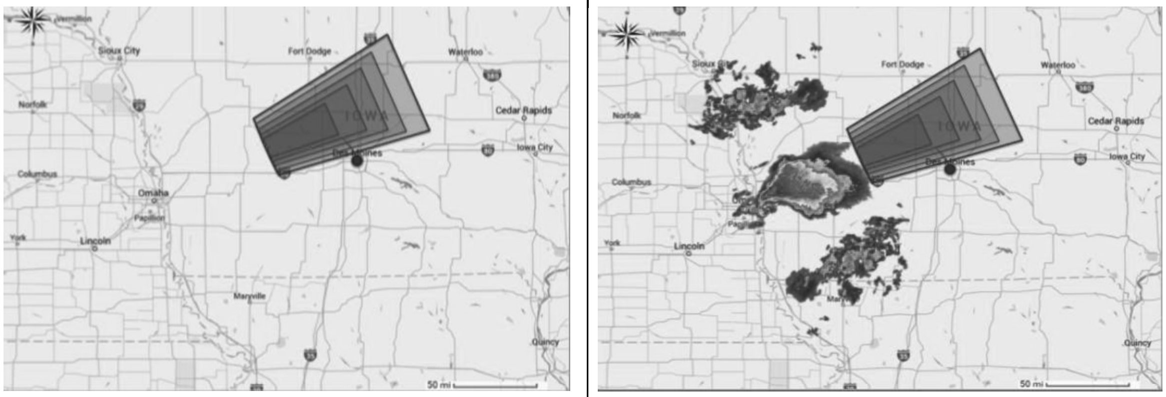
Note: The alphanumeric labels B1-I4 identify the 22 different locations of the motel in relation to the warning polygon. Specifically, the letter identifies the longitudinal transect (i.e., in the direction of storm travel) and the number identifies the lateral transect. The blue dot indicates the location of the motel which, in this scenario is located at cell H2.

Figure 2. The Four Polygon Displays



a) Deterministic Polygon

b) Deterministic Polygon + Radar Display



c) Gradient Polygon

d) Gradient Polygon + Radar Display

Figure 3. Mean p_s ratings for each grid cell*.

Figure 3. Mean p_s ratings for each grid cell*.

	A	B	C	D	E	F	G	H	I
4 (T4)	2.26/0.90 1.89/0.99 1.54/0.70 1.80/0.87				2.85/1.08 2.83/1.01 2.49/1.04 2.76/0.86				2.56/0.86 2.09/0.89 2.00/0.84 1.98/0.96
3 (T3)	2.68/1.01 2.09/0.92 2.11/0.90 1.88/0.75	3.68/0.94 3.34/1.06 3.09/0.89 2.93/0.82			3.88/1.04 3.34/1.11 3.14/1.06 2.93/0.85			3.65/1.04 3.26/1.07 3.06/0.87 2.88/0.68	2.65/0.77 2.46/1.04 2.26/0.85 2.17/0.70
2 (T2)	1.79/0.95 1.63/0.73 1.63/0.84 1.44/0.63	2.74/0.86 2.43/0.92 2.54/0.95 2.54/0.81	3.65/0.98 3.51/0.95 3.63/0.73 3.54/0.60		4.65/0.73 4.40/0.85 4.69/0.58 4.76/0.43		3.91/0.93 3.91/0.95 3.94/0.80 3.83/0.77	2.71/1.00 2.51/0.82 2.49/0.95 2.22/0.76	1.85/0.78 1.83/0.71 1.54/0.85 1.61/0.89
1 (T1)		1.88/0.91 2.03/1.01 1.63/0.77 1.76/0.86	2.53/0.86 2.74/0.93 2.54/0.92 2.44/0.95	3.74/1.02 4.43/0.78 4.29/0.71 4.12/0.64	3.74/1.05 4.11/1.13 4.77/0.55 4.83/0.67	3.62/1.02 4.49/0.74 4.54/0.61 4.34/0.66	2.68/0.94 3.63/0.81 2.97/1.07 3.10/0.92	1.65/0.69 2.43/1.17 1.77/1.14 1.73/0.78	

* The means (to the left of the slash) and standard deviations (to the right of the slash) for the four displays are listed, from top to bottom, in the order a) deterministic polygon-only, b) deterministic polygon + radar, c) gradient polygon-only, and d) gradient polygon + radar. The red cells indicate the scenarios in which the motel was inside the polygon and the gray cells indicate the locations scenarios in which the motel was outside the polygon.

Appendix A: Experiment Instructions

Severe Storm Displays

The radar display on the right shows the amount of energy reflected back to the radar from a storm. As the scale at the bottom of the image indicates, the colors change from blue through green, yellow, orange, and red as storm intensity increases. In particular, the orange and red areas in this image have more intense rainfall and are more likely to generate tornadoes.

One especially important characteristic of a storm's radar image is a *hook echo*, which indicates the circular wind rotation that signals tornado formation. It is important to recognize that a hook echo is not a perfect predictor of a tornado. Some storms with hook echoes fail to produce tornadoes and some storms without hook echoes do produce tornadoes.

Moreover, storm conditions can change rapidly, so a storm might fail to develop a tornado even though early indications suggest that it might. On the other hand, a tornado might develop rapidly in another storm that did not initially appear to be threatening. Consequently, National Weather Service (NWS) meteorologists must make their best judgment about whether the available information justifies issuing a tornado warning.

Tornado Warning Polygons

In the past, NWS meteorologists issued tornado warnings for entire counties. However, they now issue warnings in the shape of a polygon, which is intended to warn only the locations that are most likely to experience severe weather. In the example below, the NWS issued a tornado warning that affected four counties—Tuscaloosa, Jefferson, Bibb, and Shelby (outlined in red), but the area within those four counties defined by the warning polygon (outlined in white) was much smaller.

So what does this mean for you? When you become aware of a tornado warning for your area, you need to act quickly. If it is dark and ominous, find shelter immediately. If the sun is out or the weather is benign, tune to your NOAA Weather Radio or a local radio or TV station to get more details. The NWS recommends that only those inside the polygon take action. If you are ever in doubt about whether you are at risk, seek additional weather information immediately.