Role of Rain as Perception Aid in Assessing Wind Speeds and Associated Personal Risks

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(Manuscript received 22 May 2015, in final form 12 January 2017)

ABSTRACT

Extreme event perception drives personal risks and, consequently, dictates household decision-making before, during, and after extreme events. Given this, increasing the extreme event perception accuracy of the public is important to improving decision-making in extreme event scenarios; however, limited research has been done on this subject. Results of a laboratory experiment, in which 76 human participants were exposed to hurricane-strength weather conditions and asked to estimate their intensities and associated personal risks, are presented in this article. Participants were exposed to a range of identical wind speeds [20, 40, 60 mph (1 mph = 1.61 km h^{-1})] with [8 in. h^{-1} (1 in. = 2.54 cm)] and without rain. They then provided estimates of the perceived wind and rain (when present) speeds, and associated personal risks on a nominal scale of 0 to 10. Improvements in the accuracy of wind speed perception at higher speeds were observed when rain was present in the wind field (41.5 and 69.1 mph) than when it was not (45.2 and 75.8 mph) for 40- and 60-mph wind speed exposures, respectively. In contrast, risk perceptions were similar for both rain and nonrain conditions. This is particularly interesting because participants failed to estimate rain intensities (both horizontal and wind-driven rain) by a significant margin. The possible implications of rain as a perception aid to wind and the viability of using perception aids to better convey extreme weather risks are discussed. The article concludes by revisiting discussions about the implications of past hurricane experience on wind intensity perception, personal risk assessment, and future directions in extreme weather risk perception research.

1. Introduction

Aging infrastructure, increased population density, and development in hazard-prone areas have increased the number of vulnerable regions and people and the damage output of natural disasters (Barnes and Goonetilleke 2014). Hazard preparedness and resilience are complicated problems that are modulated by engineering design and sociodemographic characteristics of vulnerable regions. Perhaps the biggest challenge in increasing disaster resilience is the reliance on household decision-making irrespective of overarching policies and rules, such as building codes (Horney et al. 2010; Peacock et al. 2005). Perception of extreme weather forces is a major factor in assessing the perceived risks and individual decision-making before, during, and after disasters (Agdas et al. 2012; Slovic 1987; Trumbo et al. 2011; Webster et al. 2013). This article, which follows on from Agdas et al. (2012), reports the findings of a joint research project between psychology and civil engineering to establish a baseline for perception of extreme weather phenomena and to improve our understanding of the relationship between personal risks and decision-making. In this project, participants were subjected to mild and moderate intensities of hurricane agents, and data were collected on their perception of weather phenomena intensity, associated personal risk, and personal

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DOI: 10.1175/WCAS-D-15-0038.1

factors that affect risk perception associated with these forces.

2. Background

a. *Natural hazard risk perception, communication, and decision-making*

Wachinger et al. (2013) provides an overview of the natural hazard risk perception research. The authors cite that sociodemographic factors do not play a significant role in risk perception and preparedness but act as mediators and amplifiers, whereas a significant amount of research has focused on analyses using these factors (Lindell et al. 2005; Maldonado et al. 2015). Instead, the authors argue that people's personal experiences with natural hazards and their level of trust about sources of hazard information are the major determinants of hazard risk perception. Of these two variables, experience has been the more popular research topic, but the results of these studies have been all but consistent. For instance, there are examples of reduced perceived disaster risks because of prior experience (Elder et al. 2007); there are also examples of heightened perceived disaster risk because of earlier experiences (Knuth et al. 2014; Lazrus et al. 2012; Lindell and Hwang 2008; Solis et al. 2010) and nonsignificant relationships between experience and risk perception (Huang et al. 2015; Lazo et al. 2015). A possible reason for this has been discussed in detail by Lindell et al. (2005), and nonuniformity of experience metrics appears to be a major driver. On a similar note, Trumbo et al. (2011) discuss potential problems in coastal population increase associated with immigration and immigration of residents with no hurricane experience.

Potential hazards of shadow evacuation behavior in no-evacuation zones are also discussed in detail by Dueñas-Osorio et al. (2012). While much of the literature focuses on the potential benefits of better risk perception and increased impact of better risk assessment in improving mitigation and preparedness activities, the authors discuss the potential issues associated with shadow evacuations. The authors also discuss the discrepancies in storm surge, which is the more destructive component of hurricane forces, and wind risk perception levels. Interestingly, the mismatch between the two hazards is statistically significant for no-evacuation zones, whereas no such mismatch occurred for the evacuation zones. The authors make a compelling case for moving beyond risk perception studies and into risk behavior studies, in which behavioral patterns of risk-avoidance or risk-seeking behavior are analyzed.

Another key point in disaster management is disaster risk communication. Although there are timely advisories for different natural hazards, how people perceive and respond to these advisories depends on their knowledge of natural hazards, other sociodemographic factors, and personality traits (Cahyanto and Pennington-Gray 2015; Lazrus et al. 2012; Slovic 1996). For example, providing additional hazard risk information based on housing condition assessment was found to be instrumental in improving the effectiveness of household mitigation measures (Chatterjee and Mozumder 2014). In a similar fashion, Meyer et al. (2014) report significant knowledge gaps in residents' knowledge about Hurricanes Isaac and Sandy (severity and impact of duration), despite extensive media coverage and official advisories. The residents were simply not well informed, which ultimately affected their decision-making. Additionally, there were discrepancies between the actual hurricane threat and what residents perceived, a finding that confirms that of previous research (Dueñas-Osorio et al. 2012). Specifically, residents overestimated wind exposure while underestimating its impact, and they underestimated the impact of storm surge, which was attributed to lack of water-induced damage in hurricane damage scales and residents' lack of experience with floods as compared to winds.

Building on these research streams, this article was designed to quantitatively assess individuals' perception of different wind-driven-rain (WDR) conditions. Specifically, the research objective was to explore the impact of rain as a perception aid when estimating wind speeds, its associated personal risks, and how prior hazard experiences affect these variables. Focusing on different wind-driven-rain intensities should improve granularity of the findings and provide additional insight to the hazard perception research space.

b. *Human perception of extreme weather phenomena*

This article presents the results of experiments designed to examine perception of hurricane forces (wind and rain) and personal risks induced by these forces. The various experiments were conducted in a controlled laboratory environment at the University of Florida. Although laboratory studies of weather hazard perception have some limitations (Bottema 2000; Jackson 1978), a controlled experiment was chosen because of safety concerns associated with field experiments and the unpredictable nature of hurricanes and the resultant logistical difficulties.

PRIOR RESEARCH—WIND AND RAIN PERCEPTION

Wind perception studies date to the 1970s, following urbanization principles formed around mixed high- and medium-rise buildings and the resulting wind forces induced because of this irregular landscape. Thus, most prior research has focused on low and moderate wind speeds that are typical in urban areas. Generally called

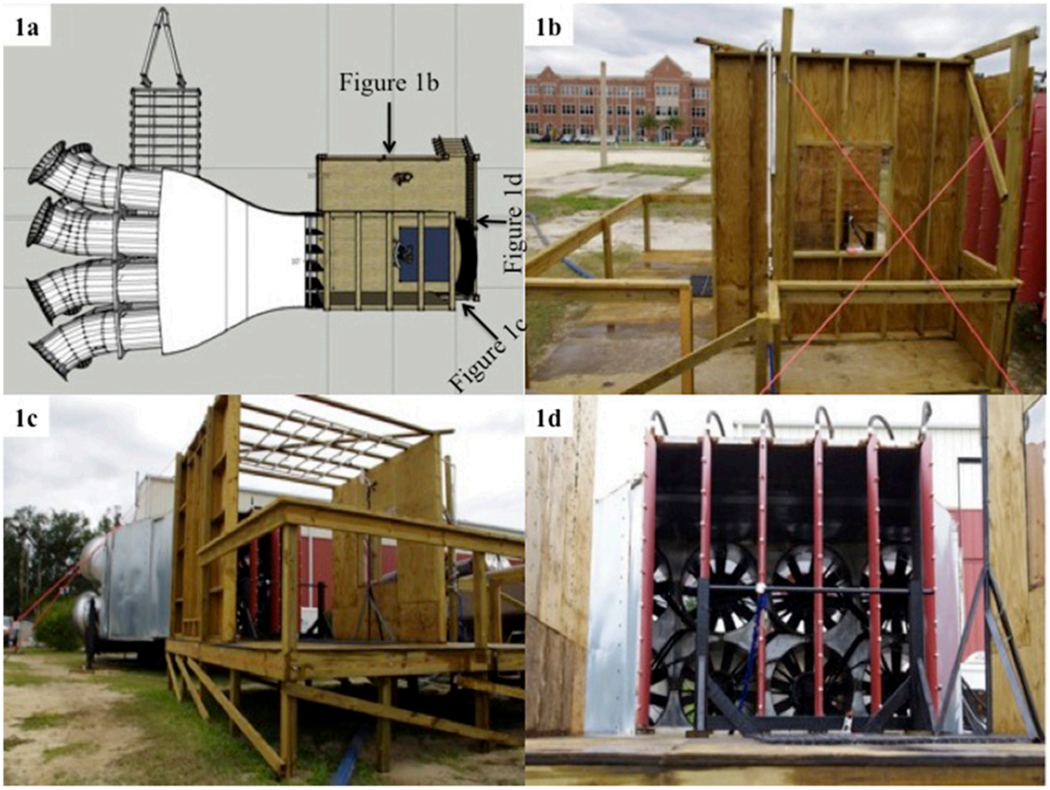

FIG. 1. (a)–(d) Hurricane simulator with the experimental observatory.

wind comfort research, these experimental studies were conducted to assess the impact of sudden gusts formed around urban areas and the effects of these gusty environments on peoples' daily lives (Bottema 2000). Experiments were performed to assess critical wind thresholds—in general speed and gustiness—that cause discomfort, make people feel unsafe, cause instability, and make daily tasks challenging (Hunt et al. 1976; Jackson 1978; Jordan et al. 2008; Melbourne 1978). To our knowledge, rain has not been experimentally studied in the same context.

3. Research gaps and limitations

Previous experimental research in human perception of extreme weather has provided some baselines, especially in the context of thresholds for discomfort and danger. Nevertheless, there are some research limitations that have prevented results from being generalized to the context of extreme weather conditions. The experiments were potentially impacted by order effects—mostly induced by technical limitations that prevented seamless randomization of wind forces—and the nature of the data collected (i.e., two-choice semantic data on human stability and comfort that prevented detailed analysis). Prior engineering research has also largely neglected the important issue of assessing personal risk during extreme weather events. Although the impacts (i.e., dynamic pressure due to velocity) and some physical effects (i.e., temperature) of the wind forces were investigated, there has not been a discrete focus on the sensation of risk induced by extreme weather forces. As identified in the literature, sociodemographic factors can influence risk perception, disaster-related decision-making, and weather-related risk perception. Current experimental design addressed these issues by (i) collecting open-ended continuous responses of weather agent intensities and personal risk scores on an ordinal scale (supplemented with sociodemographic information about participants) and (ii) randomizing experimental stimuli order at both within- and between-person levels to eliminate possible order effects.

4. Experiments

Wind, rain, and wind-driven rain were experimentally manipulated in an observatory attached to a hurricane simulator (Figs. 1a–d show the setup from different perspectives). Participants were provided protective equipment (goggles, rain jackets, etc.) and exposed to

TABLE 1. Experimental details.

Condition	Administration details	Data collected
Wind	10, 20, 30, 40, and 60 mph[a]	Wind speed and personal risks
Rain	4, 6, and 8 in. h^{-1}[a]	Rain intensity and personal risks
Wind-driven rain	20, 40, and 60 mph[a] wind, 8 in. h^{-1} rain	Wind speed and rain intensity and personal risks

[a] Randomized.

different experimental conditions. Experiment administrators recorded their responses (i.e., perceived intensities and associated personal risks). Table 1 shows details of experimental conditions and collected data characteristics.

Participants were 76 students (18 women and 58 men) aged 18 to 40 years ($M = 23.47$, SD = 4.68) from the University of Florida, some of whom had prior experience with extreme weather conditions and hurricanes. Participants were given two sets of (pre- and postexperiment) surveys, including sociodemographic questions and items on extreme weather phenomena associated with extreme-event decision-making. The results presented are produced from a larger series of experiments conducted on human perception of hurricane agent intensities (Agdas et al. 2012; Webster et al. 2013). Current results for wind-driven-rain experiments are compared to wind-only experiment results reported in Agdas et al. (2012). These data points are identified in Table 2.

a. Wind-driven-rain experiments

Participants wore protective gear (goggles, waders, and hooded raincoats) and a harness that attached to a handrail system located 8 ft (1 ft = 0.305 m) downwind of the jet, which they were allowed to hold. Participants were exposed to 20-, 40-, and 60-mph wind speeds with a constant 8 in. h^{-1} rain (simulated by a horizontal sprinkler system) for 20-s intervals in predetermined randomized orders. During the interval (~15 s) between each wind exposure, participants communicated their estimates of (i) wind speed, (ii) rain intensity, and (ii) personal risk [on a scale of 0 (no perceived risk) to 10 (dangerous)] to an observer standing outside the wind field (Fig. 1b). The test conditions (wind speed intensities, rain quantities, total exposure time, and gear) were identical for all participants; the wind speed order—as well as experiment order—was randomized to control for possible order effects.

b. Rain experiments

Participants were given protective gear (waders and raincoats) and were exposed to three different rain intensities. Between different exposures, they were asked to provide their estimates of rain intensities in inches per hour or millimeters per hour. No personal risk data are reported here because the participants reported no personal risks associated with the given rain intensities. The order of intensities was randomized to control for possible order effects.

5. Results and discussion

a. Wind-driven-rain experiments

Participants were fairly accurate in their mean wind speed estimates, which were 18.0, 41.5, and 69.1 mph for wind speeds of 20, 40, and 60 mph, respectively (Table 2). Reduced accuracy at higher speeds was expected because the perceived wind speeds were likely to be affected by the dynamic wind pressure felt, which has a quadratic relationship with wind speeds (Penwarden 1973; Penwarden et al. 1978). Interestingly, rain increased the accuracy of mean wind speed estimates at higher speeds, which were 20.6, 45.2, and 75.8 mph for 20, 40, and 60 mph in the wind-only condition [originally reported in Agdas et al. (2012)]. We argued previously that the role and potential benefits of perception aids in communicating weather phenomena intensities (Agdas et al. 2012); and the present findings seem to support these arguments. The addition of rain improved wind speed accuracy at higher speeds but did not have a significant impact on perceived risk levels. Participants reported mean risks of 4.5 and 7.3 for wind speeds of

TABLE 2. Descriptive statistics of wind and WDR experiments. The wind experiments were originally reported in Agdas et al. (2012).

	Perceived wind speed (mph)				Perceived risk on a 0–10 scale			
Actual wind speed (mph)	Range	Median	Mean	SD	Range	Median	Mean	SD
20	4–40	20.0	20.6	9.3	0–5	2.00	1.7	1.1
20 (WDR)	5–40	15.0	18.0	9.2	0–5	2.00	2.2	1.2
40	10–90	45.0	45.2	17.5	1–9	4.00	4.5	1.7
40 (WDR)	10–90	40.0	41.5	17.1	1–8	4.00	4.4	1.6
60	30–130	75.0	75.8	25.4	2–10	8.00	7.3	1.9
60 (WDR)	30–130	65.0	69.1	25.0	3–10	7.00	7.2	1.7

TABLE 3. Wind speed and risk intensity perception stratified with prior experience.

Experience metric		Perceived wind speed			Perceived risk on a 0–10 scale		
		20 mph	40 mph	60 mph	20 mph	40 mph	60 mph
Number of storms experienced	<3	19.4	42.5	71.3	2.3	4.5	7.4
	3–6	16.6	41.0	70.3	2.1	4.3	6.8
	>6	18.6	41.7	66.1	2.4	4.5	7.4
Seen a hurricane	Yes	18.2	42.0	68.8	2.3	4.4	7.1
	No	17.5	40.0	72.3	2.2	4.5	7.3
Affected by a hurricane	Yes	18.1	41.5	67.8	2.2	4.4	7.2
	No	17.8	39.0	73.0	2.4	4.4	7.3
Property damaged by wind	Yes	19.4	43.1	69.4	2.4	4.4	7.0
	No	16.7	40.2	69.5	2.1	4.5	7.3

40 and 60 mph in the wind-only condition, versus 4.4 and 7.2 for the same wind speeds in the wind-driven-rain condition. Adding water to the wind field, especially at the higher speeds, made the physical wind impact significantly more uncomfortable. These are interesting results because participants were accurate in their rain intensity estimates in neither the rain nor wind-driven-rain conditions. Although rain improved people's wind speed perception incrementally in these experiments, the actual implications can be much more significant. In these experiments, wind speeds were measured at 6-ft elevation, not the 33-ft elevation that is the standard for the hurricane wind speed measurement devices. Wind speed is not homogenous across the boundary layer and sensitive to terrain conditions where the measurements are taken. Using established conversion methods (Masters et al. 2010) would indicate an amplification factor of 1.42–1.60 for this experimental setup, which can mean different categories on the Saffir–Simpson hurricane scale for 60-mph wind speed estimates for these two experiments.

Another key finding was the relationship of prior storm experience and its association with perceived wind speeds and risks. Earlier literature indicates that previous hazard exposure may aid one in better gauging disaster impacts, and implies improved decision-making to reduce overall damage (Meyer et al. 2014; Wachinger et al. 2013). Participants were asked (i) how many tropical storms they had experienced (open ended), (ii) whether they had seen a hurricane in person (yes/no), (iii) whether they were affected by a hurricane (yes/no), and (iv) whether they had property affected by wind (yes/no). Table 3 summarizes these findings stratified by different experience metrics. Overall, more experienced participants had more accurate mean estimates when exposed to 60-mph winds, whereas experience did not have such definitive impact on perception accuracy at lower wind speeds. A similar trend was observed in risk estimates at 60-mph wind exposure for more experienced participants. The more experienced groups [measured by three two-choice questions mentioned above, questions (ii), (iii), and (iv)] reported lower risk values, which can be explained by better wind speed estimates. The more striking result is the risk-perception values as a function of the number of storms experienced, which was an open-ended question. As expected, those with the highest reported tropical storm experience had the best approximation of wind speeds at 60 mph. However, the risk-perception values at wind speeds of 60 mph did not vary as a function of prior tropical storm experience. This might be related to people's lack of understanding about what constitutes a tropical storm or hurricane, manifested by inconsistencies in their responses to similarly constructed questions about past hazard experience. Details of why this inconsistency exists are beyond the scope of this article, but detailed discussions on potential cues for this phenomenon are described in Lindell et al. (2005). Another possibility is that, although prior storm experience increases people's understanding of wind intensity, it has little effect on the psychological weight people give to perceiving risk. Thus, future research should strive to understand what individual differences might relate to people's understanding of the risk associated with extreme weather.

b. *Rain (rain-only and wind-driven-rain component) experiments*

The participants, on average, correctly identified rain intensity changes in rain-only experiments; however, they substantially underestimated the rain intensities to which they were exposed. The reported mean rainfall intensities were 1.2, 1.8, and 2.1 in. h^{-1} for horizontal rain intensities of 4, 6, and 8 in. h^{-1}. The participants were able to discriminate among intensity levels in terms of a linear trend, but their predictions substantially underestimated the actual rates. This might be because participants were simply not able to easily gauge rainfall intensity with the measurement units, although they were allowed to choose the unit with which they were most comfortable (in. h^{-1} or cm h^{-1}). The other reason for this might be due to a lack of intuitive understanding of rain intensities, when compared to wind speed estimates (Meyer et al. 2014).

In the wind-driven-rain conditions, participants also gave their estimates of the rain intensities. As expected, the perceived rain intensity (although kept constant throughout the experiments) increased with the intensified wind speeds almost linearly; however, participants' mean estimates were significantly lower than the actual intensities. The average perceived rain intensities were 1.8, 2.5, and 3.7 in. h^{-1} for 20-, 40-, and 60-mph wind speeds. The experimental results indicate that people's rain intensity predictions may follow visual and tactile cues and thus may not necessarily reflect the actual rain intensities.

6. Conclusions

This article presents concluding results from a series of preliminary experiments that studied the impact of a physically simulated hurricane environment on human perception of its agents and associated personal risks. It specifically addresses the role of rain as a perception aid and also revisits how personal experience with extreme winds or hurricanes influences people's wind speed estimates and risk perceptions. The findings from the wind-driven-rain condition support the argument that rain can improve wind perception at higher wind speeds. This is particularly interesting because participants failed to accurately interpret the rain intensities to which they were exposed. The main hypothesis in the wind experiment was that wind speed estimation was based on personal experience and dynamic pressure caused by wind forces. It is likely that, in the wind-driven-rain experiment, rain acted as a visual, auditory, or tactile wind speed perception aid. Although this is a plausible argument, additional research is necessary to support this preliminary conclusion. Future research may wish to consider asking participants about what perceptual modality they use to gauge wind speeds (e.g., visual, auditor, and tactile).

Personal experience has been identified as a significant factor in assessing hurricane intensities and a major driver of disaster risk perception. The results of this project were mostly in agreement with this notion; greater prior experience—measured by four separate questions—related to more accurate assessment of higher wind speeds and slightly reduced perceived risks. The exception, however, was the question of the results relating to prior storms experienced. People who reported to have experienced the greatest number of tropical storms reported the most accurate wind speed estimates at higher wind speeds; however, they also reported the highest personal risk when compared to those who experienced fewer storms.

These results suggest the need to move from understanding risk perception to understanding risk-taking behavior during disasters. Gaps remain in understanding the links between disaster risk perception, decision-making, and risk-seeking behavior. Risk-seeking behavior is a significant correlate of how people behave when facing hazards. Examining how individual differences in risk-seeking behavior influence hazard decision-making remains an important research question.

Acknowledgments. The authors thank the Federal Alliance for Safe Homes (FLASH; http://www.flash.org) for supporting this research. The agency had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors also thank the following engineers, technicians, and graduate students for their help in carrying out this research: Sevcan Agdas, Antonio Balderrama, Scott Bolton, Corey Cook, Kevin Frost, Alex Esposito, Amanda Gesselman, James Jesteadt, Carlos Lopez, Carlos Rodriguez, and Jason Smith.

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