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Modeling pre-evacuation delay by occupants in World Trade Center Towers 1 and 2 on September 11, 2001 ☆

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ABSTRACT

On September 11, 2001, two airplanes hit World Trade Center (WTC) 1 and 2 sixteen minutes apart, which forced one of the largest evacuations from high-rise buildings in US history. Path analysis is used to analyze telephone data obtained from WTC survivors to empirically determine if the theories from community evacuation hold true for building fires. Results show that community evacuation theories do hold true for building fires; specifically in WTC 1 and 2. In general, longer pre-evacuation times were predicted by witnessing a higher number of environmental cues, being on a lower floor in the building, obtaining more information, seeking additional information, and performing a higher number of pre-evacuation actions. A deeper understanding of human behavior in fire events can be gained by using path analysis techniques, which can ultimately improve evacuation education, training, and procedures for high-rise buildings across the world as well as future evacuation prediction techniques.

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1. Introduction

Scholars have been interested in studying occupant behavior in building fires for over half a century: this research began with Bryan in the 1950s [1], was developed and continued in the 1970s [2], was elaborated on in the 1980s [3,4] and still remains of critical importance for research in building fires today [5–7]. Over the years, the methods, theories, and research designs employed have used one of two approaches: first, researchers have spoken with evacuees from building fires and drawn relational conclusions between causes and behaviors described. Second, a more quantitative approach involves researchers interviewing evacuees using a questionnaire format and analyzing the strength of correlation between various independent and dependent variables. The knowledge resulting from these approaches has been slow to accumulate a statistical integration of all variables related to human behavior during a building evacuation, although some have come close [8,9]. Both of these techniques lack a statistical demonstration and validation of the sequential social processes of occupant behavior in fires.

Separate from building fire research, there is a field of research that studies human response to other hazards, including natural, technological, and now terrorist hazards. Formal disaster research also began in the 1950s [10,11], developed substantially through the years [12,13], and continues today [14]. Initial research methods resemble those used in the fire community. However, disaster research has advanced to use more sophisticated research designs and analysis techniques through the use of multi-staged, multi-variate models to determine the key processes of human response in disaster events[1] [15,16,17]. The key to this technique is its ability to highlight significant paths (or processes) of influence among variables while controlling all other variables in the model, which in turn removes the possibility of identifying spurious relationships between variables. Instead of simply presenting research based on bivariate analyses, which are unlikely to occur in the real world, multiple hypotheses can be tested at the same time to determine social processes that produce more powerful conclusions about the relationships between variables.

One of the key objectives of our work was to import the variables, processes, and theories from community disaster evacuation research to the World Trade Center (WTC) fire event of September 11, 2001 to empirically determine if the theories

☆ An earlier version of this manuscript appeared as Appendix C, pages 211–228, in the report: Averill, Jason D., et al., 2005. Occupant Behavior, Egress and Emergency Communications: Federal Building and Fire Safety Investigation of the World Trade Center Disaster. Gaithersburg, MD: US Department of Commerce, National Institute of Standards and Technology [14].

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[1] Exceptions: Feinberg and Johnson [8] and Sime [9] from fire research on human behavior.

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from community evacuation hold true in building fires [14]. Path analysis was used to develop an empirically based, parsimonious explanation (i.e., model) of the key factors and processes that led to occupants' delays in beginning their evacuation from the WTC Towers. This model provides a deeper understanding of human behavior in evacuation, which can explain the events of September 11, 2001. However, more importantly, this model can be used to improve evacuation education, training, and procedures for high-rise buildings world-wide as well as future evacuation prediction techniques.

Various research studies have already been performed on the WTC evacuation [14,18–20]. By writing this manuscript, we hope to encourage new research on human behavior in fire through the use of theoretical models and more sophisticated statistical analyses. We are not suggesting that the conclusions reached in this paper should be generalized to all fire events; however, we are suggesting that the technique used in this paper be incorporated into the study of human behavior in future fire events in order to establish a robust, theoretical model of human behavior in all building fires.

2. 2001 World Trade Center attack and evacuation [14]

At 8:46:30 am, American Airlines Flight 11 crashed into floors 93 to 99 of the north face of WTC 1, destroying all access to safety for the approximately 1300 occupants at or above the 91st floor. Between 8:46:30 am and 9:02 am, one of the nation's largest building evacuations began. Occupants in both WTC 1 and WTC 2 (even though their building had not been hit yet) began to assess their situation, make decisions as to what to do, perform necessary duties, and seek a route out of the building. Three minutes before the attack on WTC 2 (9:00 am), while some occupants had already begun evacuating, the first public address (PA) system announcement was made to the occupants of WTC 2 telling them to return to their offices. Then, at 9:02 am, one minute prior to the plane hitting WTC 2, a contradictory announcement was given in WTC 2 explaining that the situation was in Building 1, however, if conditions on your floor warrant, you may wish to start an orderly evacuation. It was at 9:02:59 am that a second hijacked Boeing 767, United Airlines Flight 175, struck WTC 2 damaging seven floors, from 78 to 84. With the second attack on the Towers, WTC 2 initiated a full-scale building evacuation as well. At the time that their building was hit, almost half of the occupants in WTC 2 had already exited the building; suggesting that these evacuees were actually responding to the event that had occurred in WTC 1 rather than WTC 2.

3. Evacuation theory from communities and buildings

Both community disaster and building fire evacuation research provides evidence that people do not immediately react to verbal warnings or physical cues [3,6,21]. Instead, in order to assess and confirm the initial cues, people delay their attempts to take a protective action [22]. The research also shows that characteristics of the crisis situation and of the people who experience the event influence how long an occupant delays before beginning action, such as evacuation. These characteristics are the following: (1) environmental cues, (2) proximity from safety, (3) obtaining information, (4) seeking additional information, (5) perceived risk, and (6) performing activities prior to beginning evacuation. In the case of a building fire, environmental cues are those physical cues presented to the occupants by the fire situation, including smoke, flames, heat, and debris. Proximity from safety refers to an occupant being farther away from a location of safety (i.e., out of the building). Obtaining information refers to the act of an occupant receiving information without seeking it (e.g., hearing messages, hearing other occupants discuss the event, etc.), and seeking information refers to an occupant actively seeking information from various sources (e.g., asking other occupants, calling loved ones, and/or calling 9-1-1). Perceived risk refers to occupants' perception of the seriousness of the event and how much risk/danger they feel as a result of the event. Last, performing activities prior to evacuation involves engaging in a variety of actions before moving to an exit (e.g., gathering personal items, searching for or helping others, and/or making phone calls). Relationships among these characteristics, which are posited in the path model of human behavior from the WTC evacuation, are provided using literature from the fields of disaster and fire research.

3.1. Perception of risk

Several variables have been documented as impacting the perceptions of risk that people form in a crisis. Disaster and fire studies, since the early 1960s [2,23,24] have shown that environmental cues affect a person's perception of risk [6,25,26]. What has been found to increase a person's perception of risk has been the accompaniment of environmental cues with a warning message [27–29], higher severity of the cues [7,30], and a lack of cue ambiguity [31]. For some (those in WTC 1[2] who experienced them and those in WTC 2 who witnessed them from the windows or experienced them), the cues from the WTC were dramatic and severe, with heat originating from a fireball exploding outside of their offices, leaving occupants with little room to feel safe [14]. Therefore, it was proposed that perception of risk was a direct consequence of environmental cues during the pre-evacuation period of the WTC Towers evacuation on September 11, 2001 [14].

Proximity from safety (or similarly, proximity to the event) has been studied as an influence of a person's perception of risk [24,32]. While some research has found that being farther from safety [6,31] increases a person's risk perception [33], other research has found no effect of proximity on perception of risk [30]. Occupants on the higher floors of the WTC were likely to worry about their long, rarely traveled, and disconnected stairway trip to safety [14]. Therefore, the model of pre-evacuation delay posited that the higher the floor, the higher the perception of risk [14].

Research on fires and disasters since the 1970s [34] has shown that obtaining information, such as environmental cues [35,36], warnings [37], and discussion with others around them [6], increases a person's risk perception about the event [3,38]. In the WTC, occupants were presented with multiple pieces of information, which affected their perception of the seriousness of the event [14]. Therefore, it was proposed that obtaining information leads to a higher perception of risk [14].

3.2. Seeking information

Additionally, there are specific variables that were included in the model to explain variation in occupants seeking additional information. Fire and disaster literature, since the mid 1950s [39], has found that environmental cues lead occupants to search for additional information [23,40,41], which in turn, increases their pre-evacuation time [31,42]. In building fire events, the more

[2] This sample does not include anyone at the impact floors or above in WTC 1; occupant responses had to be weighted due to a location-based non-response bias in WTC 1 [14].

ambiguous the cue, the more likely a person is to search for additional information [3,6,43,44]. Whereas some WTC occupants witnessed smoke and flames, others simply witnessed the shaking of the building or heard an explosion, leaving them to want more information [14]. Therefore, it was posited that environmental cues in the WTC led to occupants seeking additional information [14].

Although no research was found on the relationship between an individual's proximity from the exit and his/her likelihood of seeking additional information, a causal relationship can be suggested. Occupants on higher floors in the WTC Towers were required to travel long distances before reaching safety, therefore it is feasible that they sought additional information about what was going on before committing to such a lengthy and difficult task [14]. Therefore, it was proposed that proximity from the exit leads to seeking additional information [14].

Research in the fields of building fires and community disasters has found that obtaining information in an event leads to seeking additional information [45], e.g., from friends, relatives, and neighbors in a community [46] and/or from coworkers in a fire [47]. The research shows that a person is likely to confirm a message following receipt of a warning [48,49] and the more frequently the message is delivered, the more likely he/she is to actively seek more information to confirm it [50]; although not all research agrees [51]. In the WTC, occupants heard the event explained in many different ways by others inside and outside of the building, e.g., an earthquake, a ticker tape parade, and/or a terrorist attack [14]. It was posited that if WTC occupants received information about the event, they sought additional information before evacuating [14].

Risk perception influences whether individuals search for information in community-wide disasters [10] and in building fires [52]. Researchers on community evacuations have found that the higher personal risk is perceived, the more likely they are to confirm the warning message [53–55]. Research on building evacuations has found similar results [6,56]. It was hypothesized that if WTC occupants perceived their risk to be high, they sought further information [14].

3.3. Taking pre-evacuation actions

We included several relationships in the model to predict pre-evacuation actions. The influence of environmental cues on performing pre-evacuation actions has been documented in the fire evacuation research since the 1970s [41,42,57]. Being presented with cues prompts occupants to search for the cause (especially in the case of ambiguous cues) [5,43] and to search for others in the building [3]. Additionally, when occupants encounter smoke or fire, they are likely to fight the fire [2,3,23] and/or help others [6,43]. Therefore, it was posited in the WTC model that encountering environmental cues leads to performing a higher number of pre-evacuation actions [14].

Although a significant body of disaster research exists relating proximity to evacuation response [58–60], specifically stating that the farther a person is from safety (and closer to the event) the more likely they are to respond to the event [61–63], no research was found on the kinds of responses and numbers of activities performed in relation to a person's proximity from safety. The occupants in both towers had an overwhelmingly lengthy travel distance to undertake before reaching safety and were likely to engage in a variety of actions in preparation of such a long evacuation route [14]. Therefore, it was posited in the model that proximity from the exit leads to performing a larger number of pre-evacuation actions [14].

Fire researchers, since the 1970s [2,45], have shown that obtaining information and seeking additional information directly influence the performance of subsequent pre-evacuation actions. Building occupants in a fire are likely to notify and warn others of the information they received [23,40,64] as well as instruct others in what to do based on that information [3]. Occupants in the WTC were provided with information from people inside and outside of the building [14]. Therefore, in the model, both obtaining information and seeking additional information was hypothesized to lead to performing a larger number of pre-evacuation activities [14].

Last, both fire [2,40] and disaster research [58,60,65] show that a person's risk perception affects his/her pre-evacuation actions [6] and evacuating [46,66,67]. The greater the perceived risk, the more likely the individual will undertake suggested adaptive responses [16,31,37]. Research in both fields does not specify the types of actions undertaken, other than those that directly led to evacuation (e.g., gathering personal items, moving to the stair). It is hypothesized that occupants in the WTC knew that something serious had occurred in either their building or the one next door, causing them to internalize the risk to themselves [14]. Therefore, it was posited that a higher perception of risk leads to the performance of a larger number of pre-evacuation actions [14].

3.4. Pre-evacuation delay

Several variables were included in the model to predict delay in the initiation of evacuation. The impact of environmental cues on pre-evacuation delay is well documented in the fire evacuation research [3,41,57]; ambiguous cues [29,30,42,48] increase delay as people search to make meaning out of them [5,43]. Research on community evacuations has long documented [68] the same general relationship in reference to a range of different hazard types, for example evacuations at nuclear power plants [62], floods [12,17], earthquake warnings [37], volcanic eruptions [13], and many others. In WTC 1, many of the occupants observed fallen ceiling tiles, felt their building shake, and even heard what sounded like an explosion, and in WTC 2, occupants near the northwest windows saw and heard evidence of an attack (e.g., the fireball) on WTC 1 [14]. Although these cues were strong and captured the attention of occupants in both buildings, ambiguity still existed among occupants as to what was going on and what they should do, causing them to take more time to find answers. Therefore, it was posited that if occupants witnessed a higher number of environmental cues, they delayed longer before beginning evacuation [14].

Research on the influence of proximity on evacuation response has been performed since the 1970s [32,58–60]. Whereas some found that proximity from safety [62,69] affects the response of the individual [70,71], other research has found no relationship between a person's proximity and their likelihood of responding [72,73]. The majority, however, state that the farther away from safety (similarly, the closer to the event), the more likely they are to respond [61,63,74–76] and in a quicker manner [5]. Occupants higher in the building were likely to be reminded of the vast distance between them and safety, leading to a shorter time spent on their floor and in harm's way [14]. Therefore, the WTC pre-evacuation delay model posited that proximity from the exit (being higher in either building) decreases delay time [14].

Disaster researchers, since the 1950s [10,12] have found that obtaining confirmation about the event [55,77–80] and/or searching for information about the event [81,82] affects the likelihood of evacuation response [83,84], i.e., the more searching a person does for information, the higher the likelihood of response [53,85,86]. However, the more searching a person does, the longer he/she delays evacuation. Fire research shows that obtaining and searching for information actually increases pre-evacuation delay time [30,45] because searching for information takes time to complete [42,87]. Therefore, it was hypothesized that obtaining or searching for information increases pre-evacuation delay [14].

Both fire [2,40] and disaster research [58,60,65] document that a person's risk perception affects their pre-evacuation delays and response [6,46,66]. Overwhelmingly, disaster research has determined that the greater the severity of the threat and increased perception of risk, the more likely the public will respond to the message [16,37,67,75,77,88–92]. Additionally, there is research to show that higher perception of risk leads to a faster response to an incident [72,93]. However, not all research agrees. Others have found no relationship between risk perception and evacuation response [81] or speed of response [31,48]. In the WTC, it was hypothesized that if occupants' perception of risk was high, they were less likely to delay their evacuation [14].

Pre-evacuation actions and pre-evacuation delays have been linked in the fire field for decades [3]. Research into the field of pre-evacuation has determined that actions performed during this period increase an occupants' delay time [42,48,94]. It has been established that a larger number of actions performed by an occupant is associated with a longer pre-evacuation delay time [87,95]. In the Towers, many occupants gathered personal items, searched for others, and talked with colleagues before entering the stairwell [14]. Therefore, it was posited in the model that an increase in the number of actions performed extends occupants' delay times [14].

4. The model [14]

The model used to predict pre-evacuation delay in Towers 1 and 2 of the WTC on September 11, 2001 is diagrammatically illustrated in Fig. 1. The model used factors that our preliminary analyses suggested as salient and closely followed general evacuation theory.

The theoretical model presented in Fig. 1 was represented by the following structural equations.

$$X_4 = \beta_{41}X_1 + \beta_{42}X_2 + \beta_{43}X_3 + e_4$$
$$X_5 = \beta_{51}X_1 + \beta_{52}X_2 + \beta_{53}X_3 + \beta_{54}X_4 + e_5$$
$$X_6 = \beta_{61}X_1 + \beta_{62}X_2 + \beta_{63}X_3 + \beta_{64}X_4 + \beta_{65}X_5 + e_6$$
$$X_7 = \beta_{71}X_1 + \beta_{72}X_2 + \beta_{73}X_3 + \beta_{74}X_4 + \beta_{75}X_5 + \beta_{76}X_6 + e_7$$

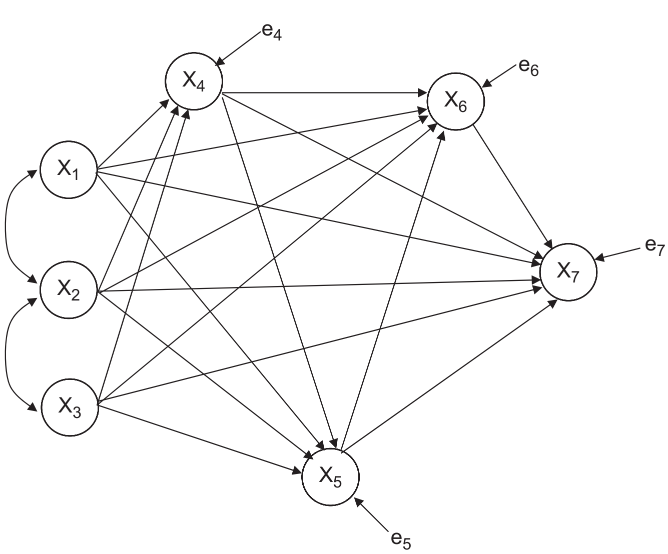

Fig. 1. Model of pre-evacuation delay. Where X_1 = environmental cues, X_2 = floor, X_3 = obtained information, X_4 = perceived risk, X_5 = sought information, X_6 = pre-evacuation actions, and X_7 = pre-evacuation delay.

where X_1 through X_7 are, X_1: environmental cues, X_2: floor in the building, X_3: obtained information, X_4: perceived risk, X_5: seeking information, X_6: pre-evacuation actions and X_7: pre-evacuation delay, β_{ii}'s represent the beta coefficients or standardized slopes for each variable, and e_4 through e_7 represent the error or residual terms for each equation.

These equations cast X_4 as a direct linear function of X_1, X_2, and X_3; X_5 as a direct linear function of X_1, X_2, X_3, and X_4; X_6 as a direct linear function of X_1, X_2, X_3, X_4, and X_5; and finally, X_7 was cast as a direct linear function of X_1, X_2, X_3, X_4, X_5, and X_6.

5. Methods [14]

5.1. Populations and samples

Two populations were selected for study. The first was all of the people who worked in WTC Tower 1 who were in the building between 8:46 am and 10:29 am on September 11, 2001. The second was the same, but for WTC 2. A comparison of occupant responses between Towers will enable us to understand the impact of information (both physical and social) and risk on pre-evacuation delay.

An enumeration of occupants' names, floor of occupancy, employer and social security number from both towers was obtained via the Port Authority of New York and New Jersey WTC badge list. A proportionate stratified sampling design was developed and the samples were stratified on two variables: building category (WTC 1 vs. WTC 2) and floor of occupancy (floors 0–43 vs. 44–76 vs. 77 and above). Secondary stratification involved the category of tenant square footage of a floor (occupants employed by tenants occupying up to 40% of a floor's square footage vs. occupants employed by tenants occupying more than 40% of a floor's square footage).

Since the badge list contained both people present in the building on September 11 and people not present in the building on the morning of the attack, an intensive screening process was used to identify "eligible" badge list members (i.e., those who were inside Towers 1 and 2 during the attacks). Occupants drawn into the sample were based on four design parameters: (1) the percentage of individuals from the badge list for whom working telephone numbers could be found (initial estimate: 80%), (2) the percentage of individuals from the badge list who were WTC 1 and WTC 2 survivors from September 11 (initial estimate: 14%), (3) the cooperation rate for screening the occupants (initial estimate: 65%), and (4) the interview response rate among September 11 survivors (initial estimate: 50%). Given these parameters, an original sample of 22 735 people from the badge list was established in order to generate the desired 800 telephone interviews. A reserve sample of 4550 people was also selected in case of unanticipated circumstances (e.g., the original eligibility rate was lower than expected).

A total sample size of 800, with an allocation of 400 to each tower, was determined to optimize statistical precision within each tower [96]. Estimates of percentages from tower-specific survey data at 400 exhibited sampling errors not greater than 2.5% points, and 98% confidence intervals of percentages are no greater than ±5% points. This level of precision was more than adequate for multivariate modeling which requires the use of *F*-tests to determine significance of the regression models.

5.2. Data collection

The interview schedule was designed to measure the following five primary areas: preparedness and training, initial September 11 experience, interim September 11 experience, evacuation experience on September 11, and respondent demographics.

Questions on preparedness and training focused on the extent to which the respondents engaged in evacuation or emergency training prior to their experience on September 11, their familiarity with the buildings, their length of employment at the WTC, and whether respondents were present at the WTC during the 1993 bombing incident. To capture their initial September 11 experience, the interview schedule contained questions on their initial awareness that something had happened in the building—where they were, what they were doing, how they first became aware, and the sources of information about the event (from their physical environment and/or others in the building). Questions regarding the respondents' interim September 11 experience focused on the time frame between when they first became aware that something had happened in the building and when they began evacuating—asking about their social environment, their physical environment, information sources, and factors that influenced their decision to evacuate. The next set of questions in the interview schedule focused on the respondents' evacuation experience by asking questions about their egress from the building, more specifically about the factors that facilitated and hindered their movement to safety. Last, information was collected on the respondents' demographics including their age, gender, language, and physical impairments.

The interview schedule was pre-tested by performing a total of 11 interviews with WTC survivors. From these 11 interviews, all aspects of the data collection procedure were evaluated, including the flow of the instrument, comprehension by the respondent, the identification of additional probes or clarifications within the questions, data coding and processing, and review of the survey data from the 11 interviews. Only minimal modifications to the instrument were needed based on the pilot interviews.

Interviews were conducted via telephone using a computer program that allowed the interviewers to collect data electronically, also known as computer-assisted telephone interviewing (CATI). All subjects received a letter in advance of the phone call that informed them of the scope and purpose of the National Institute of Standards and Technology (NIST) investigation, the purpose of the interview, and the telephone call that would follow (several days later). The letter also contained an informed consent statement. Interviewers told respondents about the confidentiality of responses, the length of the interview (approximately 20 min), and the fact that participation was voluntary. Respondents could then confirm whether they wished to participate, providing oral informed consent to the interviewer.

Interviewer training took place over 2 days and provided information to the interviewers on the purpose of the investigation, the purpose of the interview itself, and details about the interview schedule and the CATI computer program. Interviewers also listened to a NuStats professional conduct a pilot interview. Once interviewers began their own interviews for the project, they were monitored and given feedback on their interviews by a quality control supervisor.

From a total sample of 26 000 people, including both the original sample and the reserve sample, CATI interviews were completed with 803 people; of which 427 persons were in WTC 1 and 376 were in WTC 2 on September 11. The estimated response rate was 23%, using the guidelines of the Council of American Survey Research Organizations (CASRO) [97]. This response rate was driven by an inability to contact and screen eligible respondents, rather than refusals. Of the 26 000 people in the sample, interviewers were able to find contact information for 76.6%, and from this new sample, only half of the sample could be contacted for screening. The screening response rate was approximately 46%, the eligibility rate (among those who responded to the screening questions) was approximately 18%, and the interview response rate (among screened eligible subjects) was approximately 49% averaged across both towers. Of those contacted and eligible to be interviewed, only 7% refused to be interviewed.

5.3. Measurement

Seven different variables were measured and included in the WTC pre-evacuation delay model; environmental cues (X_1), floor (X_2), obtaining information without seeking it (X_3), perceived risk (X_4), seeking additional information (X_5), taking pre-evacuation actions (X_6), and pre-evacuation delay (X_7). X_1 was measured by asking respondents about the number and type of environmental cues (severe signs of danger and non-severe signs of danger) that they saw prior to initiating their evacuation. Answers to these questions were coded as dummy variables (0 or 1) and then added to form an environmental cues scale that could vary between 0 and 2. X_2 was measured by asking respondents: "What floor were you on when the event started?" Responses were coded as -7 (basement floors) to 105. Negative floor values were transposed into positive ones since this measure sought to determine how many floors people were from their building's floor of exit. Missing data was coded to the mean. X_3 was measured by asking respondents: "Now please think about the time period between when you first became aware that something had happened and when you first entered a stairwell or elevator to leave the tower. During this entire time period were you given any additional information about what was going on?" Answers were coded as a dummy variable where $1 = $ yes and $0 = $ no or missing data. X_4 was measured by asking: "During the time when you first became aware that something had happened and when you first entered the stairwell or elevator to leave did you believe that other people were in danger of being killed?" Once again, answers were coded as a dummy variable where $1 = $ yes and $0 = $ no or missing data. This measure of perceived risk was used instead of danger to self of being killed because the latter contained insufficient variance to include in the analysis. X_5 was measured by asking: "During this same time period, did you try to get additional information about what was going on?" Answers were coded a $1 = $ yes (for both successful and unsuccessful attempts to get additional information), and $0 = $ no. X_6 was measured by asking respondents if they did any of the following things: talk to another person face-to-face, gather personal items, telephone other people, continue working, save or transfer computer files, search for others, fight fire or smoke, move to another floor, or help others. These nine items were added to create a scale of taking actions (after a person first became aware that something was wrong but prior to beginning evacuation initiation) that varied between 0 and 9. Last, X_7 refers to how many minutes passed from the time when they first became aware that something was wrong until they actually began their evacuation. Their responses were coded as an interval scale of minutes that varied between (1–80) min for Tower 1, and (1–75) min for Tower 2.

5.4. Measurement reliability

The seven variables included in the pre-evacuation delay model have a high degree of reliability, based on the techniques used to measure these variables. Five of the measures, i.e., floor, environmental cues, obtaining or seeking information, and pre-evacuation activities, are event-based, fact-finding questions to which respondents tend to give consistent answers if asked more than once [98]. In addition, asking "What floor were you on when the event started?" is likely to be a reliable measure because most respondents, with the exception of visitors, are likely to have a high degree of familiarity with the floors of the building on which they work.

Risk perception has long been studied by social and behavioral scientists interested in the topic in reference to many different hazards [99] and in reference to how such perceptions of risk might impact behavior such as evacuation [13,72]. Researchers have measured risk perception in a variety of ways. However, it has become standard to measure risk perception in terms of perceived impacts to self versus others, and also in terms of near, intermediate, and long term time frames [13,37,53]. The question used to measure risk perception was selected to resemble how risk perception has been measured in other studies to maximize the measure's comparability to other research into risk perception. Risk perception was measured in terms of the near-term time element since it is the only time frame applicable to potentially impacting a building evacuation.

Regarding the more complicated measure of pre-evacuation delay, respondents were asked how many minutes passed from first awareness to beginning evacuation. Then, the respondent's reported pre-evacuation delay time was compared with landmark events (e.g., did you evacuate prior to or after WTC 2 was hit?) to ensure the reliability of that measure.

Last, error variances in the model were used to assess reliability. Due to the large amount of explained variance in the dependent variables in the equations, the error variances in the dependent variables led the authors to conclude that the measures were reliably predictive.

6. Data analysis [14]

The model of pre-evacuation delay was constructed using a quantitative method of data analysis called path analysis [100]. Path analysis provides a way for researchers to represent a set of regression equations using causal diagrams [98]. The diagrams, or path models, relate independent, intermediary, and dependent variables with single arrows indicating causation between independent (or intermediary variables) and dependent variables and double arrows indicating correlation between independent variables. Exogenous or independent variables in a path model are those with no explicit causes and can be correlated with one another. However, if two variables are too highly correlated (i.e., a correlation above 0.80), known as multicollinearity, this type of analysis should not be performed. Endogenous or dependent variables are those which have incoming arrows indicating causality with the exogenous variables. Each arrow is associated with a path coefficient (or a beta) that expresses the direct effect of an independent variable on a dependent variable in the model. In models with two or more causal variables, path coefficients are partial regression coefficients that measure the extent of one variable on another variable while controlling for all other variables in the model.

There are limitations associated with this data analysis technique. First, path analysis does not confirm causation, but rather highlights correlations that reflect theoretically supported hypotheses about causation [101]. Even with the most comprehensive model, path analysis can only suggest, rather than confirm, that one variable caused another variable for a given data set. Also, it is difficult to capture all of the influences of human behavior using this technique or any analysis technique since there is likely to be some amount of unexplained variance associated with the model equations. Last, this analysis technique is quantitative in nature and while it highlights the influences of certain types of behaviors during the pre-evacuation period, it does not explain the interpersonal and social processes involved in how these behaviors occur.

The model was populated with data from both Towers 1 and 2. The estimated model parameters included path coefficients (betas), explained variance for each equation, and other estimates. These are presented in Tables 1 and 2, respectively, for Towers 1 and 2. The estimated parameters of the models for Towers 1 and 2 revealed that the models had a high degree of success in explaining pre-evacuation delay, pre-evacuation actions, seeking information, and perceived risk in both towers. The adjusted explained variance (R^2) for perceived risk was 55% and 60% in Towers 1 and 2, respectively. The adjusted R^2 for sought information was 25% in both towers. Respectively, the adjusted R^2 for pre-evacuation actions was 68% and 69% for Towers 1 and 2. Finally, the adjusted R^2 for pre-evacuation delay in evacuation for Towers 1 and 2 was, respectively, 49% and 56%. Although studies in the physical sciences might view these values as low, these levels of adjusted explained variance are high for studies of human behavior during evacuation; and, these adjusted explained variances establish the strong predictive power of the models for both towers. All equations in the model for both towers were statistically significant at the 0.001 level or better.

Path analysis requires the basic assumptions of regression. Therefore, the models were assessed for conditions that would negatively influence whether the basic regression assumptions could be made, including specification error, multicolinearity (when two or more independent variables are highly correlated [98]), nonlinearity and heteroscadasticity [98] (i.e., the extent to which the error term varies with the values of the independent variable). Also, the authors assessed whether the estimated model parameters were unbiased [102]. Specification error was not determined to be a problem. The model included only major variables of import suggested by evacuation theory, and excluded variables shown in the preliminary analyses as non-predictive in the data sets being analyzed.

Table 1
Estimated parameters of the model for Tower 1[a].

Variables		Path			Equation	
Endogenous	Exogenous	Coefficient	Estimate	$\propto$	$\propto$	R^2
X_4	X_1	β_{41}	0.38	0.00	0.00	0.55
	X_2	β_{42}	0.37	0.00		
	X_3	β_{43}	0.14	0.00		
X_5	X_1	β_{51}	0.21	0.00	0.00	0.25
	X_2	β_{52}	0.21	0.00		
	X_3	β_{53}	0.01	N/S		
	X_4	β_{54}	0.15	0.02		
X_6	X_1	β_{61}	0.27	0.00	0.00	0.68
	X_2	β_{62}	0.41	0.00		
	X_3	β_{63}	0.05	0.06		
	X_4	β_{64}	0.08	0.04		
	X_5	β_{65}	0.20	0.00		
X_7	X_1	β_{71}	0.29	0.00	0.00	0.49
	X_2	β_{72}	−0.17	0.00		
	X_3	β_{73}	0.20	0.00		
	X_4	β_{74}	−0.02	N/S		
	X_5	β_{75}	0.10	0.01		
	X_6	β_{76}	0.47	0.00		

[a] Where X_1 = environmental cues, X_2 = floor, X_3 = obtained information, X_4 = perceived risk, X_5 = sought information, X_6 = pre-evacuation actions, and X_7 = pre-evacuation delay.

Table 2
Estimated parameters of the model for Tower 2[a].

Variables		Path			Equation	
Endogenous	Exogenous	Coefficient	Estimate	∝	∝	R^2
X_4	X_1	β_{41}	0.30	0.00	0.00	0.59
	X_2	β_{42}	0.49	0.00		
	X_3	β_{43}	0.12	0.00		
X_5	X_1	β_{51}	0.25	0.00	0.00	0.25
	X_2	β_{52}	0.11	N/S		
	X_3	β_{53}	0.07	N/S		
	X_4	β_{54}	0.17	0.02		
X_6	X_1	β_{61}	0.20	0.00	0.00	0.69
	X_2	β_{62}	0.36	0.00		
	X_3	β_{63}	0.07	0.04		
	X_4	β_{64}	0.23	0.00		
	X_5	β_{65}	0.17	0.00		
X_7	X_1	β_{71}	0.13	0.01	0.00	0.56
	X_2	β_{72}	−0.19	0.00		
	X_3	β_{73}	0.23	0.00		
	X_4	β_{74}	0.05	N/S		
	X_5	β_{75}	0.11	0.01		
	X_6	β_{76}	0.51	0.00		

[a] Where X_1 = environmental cues, X_2 = floor, X_3 = obtained information, X_4 = perceived risk, X_5 = sought information, X_6 = pre-evacuation actions, and X_7 = pre-evacuation delay.

Table 3
Zero-order correlation matrix for Tower 1[a].

	X_1	X_2	X_3	X_4	X_5	X_6	X_7
X_1	1	0.68	0.25	0.67	0.45	0.71	0.59
X_2	–	1	0.26	0.67	0.45	0.76	0.46
X_3	–	–	1	0.34	0.17	0.29	0.37
X_4	–	–	–	1	0.43	0.64	0.47
X_5	–	–	–	–	1	0.55	0.44
X_6	–	–	–	–	–	1	0.64
X_7	–	–	–	–	–	–	1

[a] Where X_1 = environmental cues, X_2 = floor, X_3 = obtained information, X_4 = perceived risk, X_5 = sought information, X_6 = pre-evacuation actions, and X_7 = pre-evacuation delay.

The models for both Towers 1 and 2 were assessed for multicolinearity in two ways: (1) zero-order correlation matrices for both models (see Tables 3 and 4) were inspected to confirm that none of the correlations between the regressors were around 0.80 or higher and (2) each exogenous variable (a variable without explicit causes in the model) was regressed on all other exogenous variables in that equation to verify that the explained variances for these regressions were not approaching 1.00. The zero-order correlation matrices list the correlations between all of the variables in the models and these can be inspected by readers for information about how each of the variables are correlated at the bivariate level. The conclusion was made that multicolinearity was not a source of bias in the estimated parameters of the model in either the data set for Tower 1 or 2.

The models were then assessed to determine if the assumption of linearity could be met by transforming exogenous variables in each equation to alternative nonlinear forms. These transformed variables were then correlated with each of the pre-determining and endogenous variables (variables with explicit causes in the model) in both models. None of the correlations involving the transformed exogenous variables increased substantially beyond the linear correlations presented in Tables 3 and 4.

Table 4
Zero-order correlation matrix for Tower 2[a].

	X_1	X_2	X_3	X_4	X_5	X_6	X_7
X_1	1	0.60	0.43	0.64	0.46	0.67	0.56
X_2	–	1	0.44	0.72	0.41	0.75	0.48
X_3	–	–	1	0.46	0.30	0.47	0.55
X_4	–	–	–	1	0.44	0.72	0.55
X_5	–	–	–	–	1	0.53	0.47
X_6	–	–	–	–	–	1	0.68
X_7	–	–	–	–	–	–	1

[a] Where X_1 = environmental cues, X_2 = floor, X_3 = obtained information, X_4 = perceived risk, X_5 = sought information, X_6 = pre-evacuation actions, and X_7 = pre-evacuation delay.

Table 5
Observed means, standard deviations, and ranges[a].

Variable	Tower 1			Tower 2		
	M	SD	Range	*M*	SD	Range
X_1	0.84	0.73	2.00	0.68	0.70	2.00
X_2	41.87	25.71	90.00	48.99	30.56	104.00
X_3	0.11	0.32	1.00	0.21	0.41	1.00
X_4	0.63	0.48	1.00	0.67	0.47	1.00
X_5	0.28	0.44	1.00	0.29	0.45	1.00
X_6	2.08	1.50	7.00	2.37	1.46	8.00
X_7	5.61	8.34	79.00	6.04	8.06	74.00

[a] Where X_1 = environmental cues, X_2 = floor, X_3 = obtained information, X_4 = perceived risk, X_5 = sought information, X_6 = pre-evacuation actions, and X_7 = pre-evacuation delay.

Finally, the assumption of homoscedasticity (i.e., the error term is constant for all levels of the independent variable) was assessed by visual inspection of regression residuals in scatter plots for each relationship in both models; and it was concluded that this assumption was met. The observed means, standard deviations, and the ranges for all of the variables included in the models for both towers are presented in Table 5.

7. Findings [14]

Even though different situations and timelines were presented to occupants in WTC 1 and 2, similar findings emerged in Towers 1 and 2, with a few exceptions. This lends validity to the conclusions that can be drawn from the analyses. First, we consider each of the four equations in both models for both towers (see Fig. 1), and then the models are interpreted as a whole so that the most significant paths of influence for each tower can be distinguished.

7.1. Predicting perceived risk

The findings that emerged regarding predicting risk perception were virtually identical across the two towers. In Tower 1, both environmental cues and floor had strong and similar impacts on predicting perceived risk, respectively, β_{41} and β_{42} were 0.38 and 0.37, while obtained information had a weaker but statistically significant impact ($\beta_{43} = 0.14$). In Tower 2, both environmental cues and floor had strong impacts on predicting perceived risk, respectively β_{41} and β_{42} were 0.30 and 0.49, and obtained information had a weaker but statistically significant impact ($\beta_{43} = 0.12$). These findings suggest that the risk that people perceived before they began their evacuation increased largely as a function of floor height and being presented with environmental cues (both in their building and from the outside building). It is most likely that floor had an effect on risk perception due to the perceived increased time needed to evacuate as a result of being higher in WTC 1 (the affected tower) and WTC 2 (concerned that the same may happen in their building). Related to this, environmental cues likely increased risk perception since seeing, hearing, and feeling the physical cues that indicate danger make discounting danger—most people's natural inclination—harder to achieve. Obtained information, with a lesser effect, likely increased perceived risk because people learned more about the seriousness of the event through the information obtained.

7.2. Predicting seeking information

Once again, the findings that emerged for predicting seeking information were almost identical across both towers. In Tower 1, environmental cues and floor both had the strongest and identical impacts on seeking information, β_{51} and β_{52} were both 0.21; obtained information had no impact on seeking information, β_{53} was not statistically significant; and perceived risk had a slight impact on seeking information ($\beta_{54} = 0.15$). In Tower 2, environmental cues had the strongest impact on seeking information ($\beta_{51} = 0.25$); the impacts of floor and obtained information, β_{52} and β_{53}, were not significant; and perceived risk had a slight impact on seeking information ($\beta_{54} = 0.17$). Seeking information in times of rapid onset emergencies is a typical human response since people need to interpret and make sense out of an event before they act on it. The finding that environmental cues were the strongest predictor of seeking additional information is consistent with evacuation theory and milling behavior. Obtained information had no impact on seeking additional information in either tower. Perceived risk had a similar effect on seeking information—albeit lesser of an effect than environmental cues—in both towers, likely because it increased the urgency people had to interpret the situation. Interestingly, floor height (or distance from the exit) had a significant effect on seeking information in Tower 1, but not in Tower 2. Evacuation theory would predict that this effect would be present for Tower 1 since it was struck first, and most people in Tower 2 had begun evacuation before their own tower was hit.

7.3. Predicting pre-evacuation actions

In both towers, the strongest predictor of taking pre-evacuation actions was floor: β_{62} in Tower 1 was 0.41 and it was 0.36 in Tower 2; likely because of the need to prepare for the long travel distance. Environmental cues were also predictive of pre-evacuation actions, β_{61}, respectively, in Towers 1 and 2 was 0.27 and 0.20. Once again, observing cues that one is at risk and being high in the building (farther away from safety) emerged as strong predictors of taking pre-evacuation actions. Obtaining information had virtually no impact in either tower; β_{63} was 0.05 in Tower 1 and 0.07 in Tower 2. Seeking information impacted pre-evacuation action, β_{65} was 0.20 in Tower 1 and it was 0.17 in Tower 2; likely because the additional information prompted evacuees to prepare further before moving to the stair. Finally, the impact of perceived risk on taking pre-evacuation actions (β_{64}) was 0.23 in Tower 2, but it was weaker in Tower 1 (0.08).

7.4. Predicting pre-evacuation delay

The impacts of environmental cues (β_{71}), floor (β_{72}), obtained information (β_{73}), perceived risk (β_{74}), sought information (β_{75}), and pre-evacuation action (β_{76}) on pre-evacuation delay, respectively, were 0.29, −0.17, 0.20, −0.02, 0.10, and 0.47 for Tower 1; and for Tower 2 they were 0.13, −0.19, 0.23, 0.05, 0.11 and 0.51. The greatest predictor of pre-evacuation delay in both towers was taking pre-evacuation actions. Obviously, doing any action before initiating evacuation delayed departure. Setting this factor aside, some clear differences emerged between the two towers in terms of the relative impacts of the remaining variables in the model. Perceived risk (β_{74}) had no direct effect on pre-evacuation delay. This finding is consistent with general evacuation theory where perceived risk's impact on actual behavior is indirect through other factors. The three factors with the strongest direct effects on pre-evacuation delay were the same in both towers; environmental cues (from inside and outside of the building), floor, and obtained information. In both towers, floor's effect was negative, meaning the higher the floor; the quicker people were to initiate their evacuation. Environmental cues and information received both increased pre-evacuation delay. Finally seeking additional information had an impact on pre-evacuation delay.

7.5. WTC pre-evacuation delay models

The dominant paths in explaining pre-evacuation delay in both Tower 1 and 2 are environmental cues (information from the physical environment that something was terribly wrong—even in another building) and floor (increased distance from safety) led people to find additional information, most likely information about what was going on and what they should do. Next, the act of seeking additional information, that is "milling" to make sense out of the situation, led people to take actions to prepare to evacuate. Finally, taking those actions to prepare to evacuate delayed the initiation of actually evacuating. In addition to this multi-step process, environmental cues and floor also had indirect impacts on pre-evacuation delay through other factors as follows. Both factors increased the odds of seeking information and both factors increased the chances that people would take pre-evacuation actions to get ready to leave. Both factors also had direct impacts on actual pre-evacuation delay. Witnessing a higher number of environmental cues increased delay while being on a higher floor decreased it. It is likely that occupants who encountered environmental cues in their building spent time dealing with the cues and occupants who witnessed WTC 1 cues from their own building in WTC 2 spent time watching and discussing them on their office floors. On the other hand, occupants higher in both buildings, even though they performed a higher number of actions, may have thought that their distances to safety did not provide them with any other option than to perform these quickly and leave in a shorter period of time. Finally, obtaining additional information about the event without seeking it had a direct impact on increasing pre-evacuation delay. This could be because it took time to listen to information.

The key causal paths that led people to delay in the evacuation of Tower 2 were identical to those discerned in Tower 1, but there was one decided difference. In Tower 2, perceived risk was predicted by environmental cues and floor and also contributed to seeking additional information and taking pre-evacuation actions, while the effect of perceived risk was substantially lower in Tower 1. This was likely the case because Tower 1 was hit without warning, and only the occupants in Tower 2 had time to contemplate about (and perceive) their own risk and danger.

8. Conclusions

Path analysis was performed on data collected from the September 11, 2001 evacuation of the WTC Towers [14]. This analysis not only determined the factors that influenced pre-evacuation delay (i.e., environmental cues, floor, obtaining information, perception of risk (indirectly), seeking information, and performing pre-evacuation activities), but also proved that the theories from community evacuation hold true in building fires. Theories on behavior from community evacuations can be used to understand behavior in building fires in order to make occupants safer in case of future events.

The authors hope that this analysis will assist in directing new research on human behavior in fire through the use of theoretical models and more sophisticated statistical analyses. The technique used in this paper should be incorporated into the study of human behavior in future fire events in order to establish a robust, theoretical model of human behavior in all building fires. There are many benefits to multi-variate modeling, including (1) the ability to draw conclusions about the relationship between any two variables in a model while controlling for the influence of every other variable in the model, (2) a method to synthesize findings across events into models that summarize empirically based research findings; (3) an empirical way to distinguish between factors that have only slight impacts on human behavior from those with great influence; and (4) a technique to discern the paths of greatest influence in understanding the multi-staged social processes that underlie occupant responses to building fires.

Additional research is needed on human behavior during evacuations. First, data should be collected from different types of building fires; for example, in situations where the environmental cues present are not as strong as they were in the WTC Towers. Also, researchers should use measurement techniques that will capture a wider range of variables, such as details about the occupants' past experiences. Finally, research should include a mixture of quantitative and qualitative data so that the latter can be used to flesh out the trends missed by the quantitative analysis.

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