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Article

Impact of Virtual Reality on Decision-Making and Risk Assessment During Simulated Residential Fire Scenarios

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Abstract: Recent research has used virtual environments (VEs), as presented via virtual reality (VR) headsets, to study human behavior in hypothetical fire scenarios. One goal of using VEs in fire scenarios is to elicit patterns of behavior which more closely align to how individuals would react to real fire emergency situations. The present study investigated whether elicited behaviors and perceived risk varied during fire scenarios presented as VEs via two viewing conditions. These included a VR condition, where the VE was rendered as 360-degree videos presented in a VR headset, and a screen condition, where VEs were rendered as fixed-view videos via a computer monitor screen. We predicted that the selection of actions during the scenario would vary between conditions, that participants would rate fires as more dangerous if they developed more quickly and when smoke was rendered as thicker, and that participants would report greater levels of immersion in the VR condition. A total of 159 participants completed a decision-making task where they viewed videos of an incipient fire in a residential building and judged what action to take. Initial action responses to the fire scenarios varied between both viewing and smoke conditions, with those assigned to the thicker smoke and screen conditions being more likely to take protective action. Risk ratings also varied by smoke condition, with evidence of higher perceived risk for thicker smoke. Several factors of self-reported immersion (namely 'interest', 'emotional attachment', 'focus of attention', and 'flow') were associated with risk ratings, with perceived presence associated with initial actions. The present study provides evidence that enhancing immersion and perceived risk in a VE contributes to a different pattern of behaviors during simulated fire decision-making tasks. While our investigation only addressed the ideas of presence in an environment, future research should investigate the relative contribution of interactivity and consequences within the environment to further identify how behaviors during simulated fire scenarios are affected by each of these factors.

Keywords: fire; smoke; human behavior in fire; virtual reality; growth rate; immersion

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Citation: Russell, M.D.; Bonny, J.W.; Reed, R. Impact of Virtual Reality on Decision-Making and Risk Assessment During Simulated Residential Fire Scenarios. *Fire* **2024**, 7, 427. https://doi.org/10.3390/fire7120427

Academic Editors: Wei Xie, Eric Lee, Yuchun Zhang and Tao Li

Received: 8 October 2024
Revised: 15 November 2024
Accepted: 20 November 2024
Published: 22 November 2024

1. Introduction

In 2022, there were approximately 350,000 residential fires, leading to almost 3000 fatalities in the U.S. [1]. To aid in minimizing casualties in such situations, it is important to understand how individuals react to fire and perceive the risk that a fire presents. This requires researchers to place the individual in a world that can be perceived as real and that resembles real fire situations. A controlled, yet realistic, environment may allow for realistic responses while maintaining psychological and physiological safety for participants [2]. The present study evaluated how the behaviors of individuals were impacted by using virtual reality (VR) to display a simulated residential fire scenario.

1.1. Connecting Fire Characteristics to Human Behavior

Research has indicated that individuals use a number of factors and cues, such as flame height and smoke output, when determining the risks posed by a fire [3–10]. These impact the sequence of behaviors individuals take during a fire event. The Protective

Action Decision Model (PADM) details the actions individuals take, in sequence, during an event [11–14]. Kuligowski [15] describes how, in the PADM, the pre-movement decision-making process is divided into four phases. Phase 1 is the perception of cues. In a fire event, this could include the introduction of smoke, flames, or an alarm to the individual's senses. Phase 2 is the interpretation of the situation and the risk the cues pose. In Phase 3, the individual identifies and evaluates the set of possible actions and selects one to perform. Phase 4 is the transition into taking the chosen action, which ends the pre-movement phase of the process. Depending on the actions chosen and the situation, the individual may repeat this decision-making process multiple times during an event. To evaluate models of human behavior in fire, including the PADM, the collection of data regarding both occupant actions and the corresponding characteristics of the presented fires is required.

1.2. Approaches for Collecting Occupant Behavior

Data on human behavior in fire (HBIF) has been primarily gathered in two ways: post-fire event interviews and laboratory experiments. Each approach has relative strengths for connecting behavior to fire characteristics with regard to external and internal validity. In behavioral science, research higher in external validity entails that behaviors recorded during a study are likely to be observed in the real world. Studies that are higher in internal validity are more likely to be able to identify factors that cause changes in behavior, due to experimenter control. In the case of the post-incident interviews, individuals that survived a fire incident are presented with surveys that prompt them to recall aspects of the incident to understand what they experienced within the fire situation and how they responded. This type of field research is high in external validity as recorded behaviors are from the real world. However, these studies tend to be lower in internal validity due to lack of researcher control and sources of bias. For example, since only survivors can be interviewed, this introduces a bias into survey results derived from surviving a fire event [16,17]. Additionally, emotional events can lead to memory encoding retrieval bias which can influence the survey responses [16–18]. Despite these biases, results from post-incident surveys have informed the behaviors of occupants during real events and associations with fire and context characteristics [15].

Laboratory-based methods, such as hypothetical fire situations, have been implemented to increase the control of situational factors when studying human behavior in fire. In this type of research participants are typically presented with hypothetical or simulated fire situations and then participant judgments about the situations are recorded. For example, videos of simulated and real fires have been presented to participants via computers and their responses recorded [19–21]. An advantage of laboratory studies over field research is the higher level of internal validity due to the ability of the researcher to control and test the causal impact of factors on behavior. However, a primary concern with laboratory-based methods is the external validity of the results [2]; judgments participants make about hypothetical fire scenarios on a computer may not align with how occupants behave in real fire events. Prior research holds that participant reactions to fire incidents are based not solely on the fire characteristics, but also on the environment in which an individual finds themselves during such incidents [3,4]. The challenge faced by researchers is to evoke feelings similar to those experienced during a fire event without the possibility of real harm to the individual.

1.3. Virtual Environments and HBIF

The use of virtual environments (VEs) allows a malleable environment in which to study HBIF that can address some of the external validity concerns of laboratory research. In a laboratory environment, the cues received by an individual can be controlled and altered so that their influence on the action taken can be studied. This has typically been achieved by presenting text-based descriptions of a fire scenario, sometimes including videos of fires, on computer monitors. In a VE, the researcher can present the individual with the visible and audible cues of a fire while maintaining the safety of the participant. A distinction from stimuli used in prior laboratory-based HBIF research is that VEs allow for greater immersion and interaction during a fire scenario. By incorporating the potential immersive and interactive functionality of VEs into laboratory experiments, it is possible that participants experience the simulated fire more fully and thus the perceived risk may be more acute. We postulate that the more immersive the VE, the more realistic the cues feel, and thus, the perceived risk and resulting actions could be more realistic.

Prior research has examined the use of virtual reality (VR) to render VEs as part of safety training programs. VR devices have been used in a number of emergency training situations to help better instruct individuals on how to react to said situations without actually posing danger to the individual [22–25]. This training can better prepare the individuals to handle the emergency as they allow for the recreation of scenarios including buildings and evacuation routes [24]. This research has observed that this type of training can be effective in preparing individuals and responders for these events [23]. With evidence that VR can enhance at least some aspects of safety training outcomes, it may also enhance hypothetical scenarios when examining HBIF.

Human–computer interaction research has provided evidence that using VR systems to render VEs can enhance immersion. When a person reports high levels of immersion with an experience, they are described as being encapsulated in the experience, minimizing extraneous factors from the real world such as noise and other distracting stimuli [26,27]. In highly immersive experiences, the VE can be used by researchers to replace the physical world [2]. VR systems have been designed to imbue a VE with a high level of immersion. To do so, VR systems use headsets, equipped with screens and lenses, to visually render a VE while obscuring visual input from the real world. Additional functionality can be integrated with VR systems to allow for 360-degree projections, where a user turns the headset to visually reveal more of the VE; audio via headphones; and interactivity, where the user can physically walk with that movement translated to the VE, as well as the use of handheld controllers [27]. This allows for VEs to be rendered in VR in a way that aligns with what the individual may experience in a real-world situation. Indeed, as applied to HBIF research, it has been proposed that using VEs and VR could enhance the immersion of lab-based research scenarios and the external validity of observed behaviors [2].

The goal of using VR in HBIF studies is to improve and enhance behavioral realism in participant responses. In fire safety research, behavioral realism refers to behaviors exhibited by participants in laboratory research aligning with actions occupants take in real fire incidents [2]. By using VR to create simulations in which participants can visually experience smoke and fire, the objective is to facilitate behavioral realism, increasing the external validity of laboratory research [2,28,29]. Arias et al. [2] detail a number of factors to consider when addressing behavioral realism, which include immersion, interactivity, and consequences. The present study primarily focuses on immersion and the potential for improved immersion when using VR simulations of VEs compared to video-based stimuli. Georgiou and Kyza [30] explain that total immersion in a simulated environment can be broken into two separate factors: presence and flow. Presence is the feeling of being surrounded by a realistic environment, even though it is a virtual one [30]. Flow is the full absorption into the activity by the participant [30]; the participant not only feels a part of the world, but they are also fully enveloped in it. The goal in creating a more immersive environment is to increase the level to which participants suspend disbelief and give responses that resemble real-world responses. In digital media, the suspension of disbelief refers to when a user is compelled by a fictional world to temporarily accept the virtual environment as reality [31]. With regard to VR, it has been proposed that immersive environments can contribute to the suspension of disbelief in simulated scenarios [32].

The second factor considered by Arias and colleagues [2] for behavior realism is interactivity within the environment. The process of allowing individuals to be involved in, and influence, the environment should be considered when creating an environment. Interactivity is the process by which participants or individuals take part in the simulation. Participants can become frustrated, and thus less immersed, if they do not feel they can influence the VE sufficiently. Finally, Arias et al. [2] state that consequences (i.e., physical or psychological ramifications to the participant) for the individual must be carefully considered to maintain behavioral realism. Since there is no physical danger to the participant within the VE, the lack of consequences could cause them to make decisions that differ from those made in a real-world situation. By creating virtual consequences that more closely resemble real-world consequences, behavioral realism is more likely to be achieved [2].

1.4. Simulated Fires

Keeping the factors that lead to behavioral realism in simulations in mind, it is important to present participants with VEs that can effectively provoke the desired realism in responses. In HBIF research, this includes the presented fire. Tools such as the Fire Dynamics Simulator [33], PyroSim [34], and Smokeview [35] allow for the creation of fire simulations that depict fires with realistic dynamics. As such, simulated fires with realistic dynamics present a VE that can potentially bring about both realistic perceptions of risk and appropriate action sequences to a fire as a result [2]. Using tools such as the FDS, one can model fires that allow the experimenter control over characteristics of the fire (e.g., smoke output, flame height) and the building environment. This allows the study of these characteristics in a VE where participants are immersed in the study to the greatest extent possible.

1.5. Present Study

The present study investigated whether the presentation method of a VE to a participant affected behavioral responses during a simulated fire scenario. The goal was to better understand human behavior in fire scenarios for use in fire safety training and fire emergency preparedness. The current study focuses on participant responses when viewing fire simulations on a computer screen versus participants viewing the same simulations in a 360-degree VR environment. We told participants about the situations into which they were being placed to give them a more informed sense of actions that may be taken given the current state of the fire. A VR condition where participants viewed 360-degree videos via VR headsets and a screen condition where they were viewed on computer monitors as traditional videos were used to present simulated fires. Fires were manipulated with regard to growth rate in intensity and smoke opacity, with the aim of comparing responses to the virtual fire simulations presented in the study to prior effects observed with fire cues. Through this, we sought to investigate the following hypotheses. First, we predicted that participants' selection of actions taken during the simulated fire decision-making task would vary from the VR condition to the traditional viewing condition and when manipulating fire characteristics. Second, we predicted that participant ratings of fire danger would be higher when the fire rendered had a higher growth rate versus a slower growth rate and when it had smoke that was rendered as thicker versus thinner. Finally, we hypothesized that participants would report higher levels of immersion when viewing the simulations in the VR condition than those who viewed the scenario in the traditional, on-screen method.

2. Materials and Methods

2.1. Participants

A total of 159 participants, recruited from an online platform (Prolific.com), were used in this study. The mean age of the participants was 37.60 years, and of the 159 that responded, 102 of them indicated that their biological sex was male. The present study utilized a 'bring-your-own-device' approach, recruiting participants that owned VR devices and were willing to use them as part of an online research study. All participants were asked to complete a prescreening survey to determine eligibility including being located within the United States, owning a VR headset, having used a VR headset at least once before, being fluent in English, and having normal or corrected-to-normal vision. Based on the prescreen survey, 464 responses were eligible for the main study, with the types of

VR devices reported by those that owned a system being Meta Quest 2 (N = 149), Oculus Quest 2 (N = 128), Meta Quest 3 (N = 54), Oculus Rift (N = 50), other (N = 33), HTC Vive (N = 16), Oculus Rift S (N = 14), Valve Index (N = 9), HTC Vive Pro (N = 4), HP Reverb G2 (N = 2), HTC Vive Focus Plus (N = 2), HTC Vive Pro 2 (N = 2), and HTC Vive Focus 3 (N = 1). Eligible participants were invited to complete the main study and informed of the nature of the task (i.e., they would be shown simulated fires). Participants were then randomly assigned to either the VE or screen conditions.

Monetary compensation (USD 15 per hour) of the participants was given upon completion of the study through Prolific (approximate duration of the study was 3 min for the prescreen survey and 15 min for the main task). All human subject protocols were followed and reviewed by the local institutional review board. Informed consent information was collected before participation in the experiment was permitted.

2.2. Materials

For this study, participants were presented with videos from an online collection of fire simulations [36]. The environment selected for the present study was a living room, furnished to contain items typically observed in this type of room (Figure 1). Participants viewed the videos in either a 360-degree VR photosphere (N = 76) or in a traditional, 2D, on-screen view (N = 83). Characteristics of the fires were manipulated across participants. Using a t2 curve [37], two separate growth rates were used to create a slower- (alpha = 0.024) and faster-growing (alpha = 0.188) fire. The opacity of smoke was manipulated in PyroSim and presented either as thin (more transparent) or thick for each fire simulation [30]. For each fire simulated, PyroSim was also used to render the growth rate and smoke opacity conditions in both a 360-degree and a traditional video [34]. VR condition participants were able to view the 360-degree video by rotating their head and have the change correspond to a change in view within the rendered video in the headset. All simulations, across growth rate conditions, started with the same intensity, where the simulated heat release rate was 277 kW.

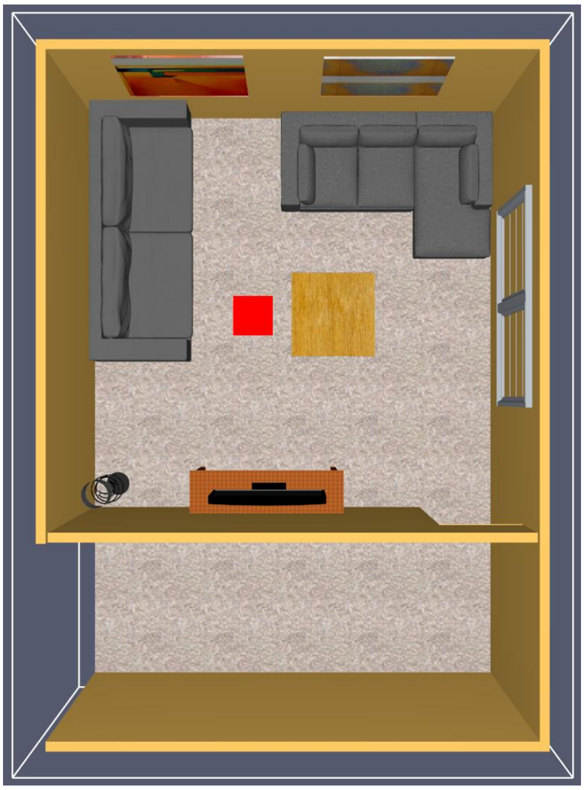

Figure 1. Top view of the virtual environment presented during the experiments (red square indicates the location of the fire).

To measure immersion among participants, we used a modified version of the Augmented Reality Immersion (ARI) scale. The ARI uses 3 subscales with which to measure levels of immersion in augmented reality (AR) situations [30]. These subscales are further broken into two more factors each, resulting in a total of six factors used in analyzing immersion [30]. Our modified version was given to both groups of participants to measure levels of interest (e.g., "*I liked the activity because it was novel.*"), usability (e.g., "*It was easy for me to use the AR application*."), emotional attachment (e.g., "*I was curious about how the activity would progress.*"), focus of attention (e.g., "*If interrupted, I looked forward to returning to the activity*."), presence (e.g., "*The activity felt so authentic that it made me think that the virtual characters/objects existed for real*."), and flow (e.g., "*I didn't have any irrelevant thoughts or external distractions during the activity*."; [30]). Participants were asked to respond to each item on a 7-point Likert-type scale to indicate to what extent they agreed (7) or disagreed (1) with each. Item 18 ("*I was so involved that I felt my actions could affect the activity*" [30]) was not used in the present study.

2.3. Procedures

All tasks for this experiment were hosted online via a JATOS server and were coded using HTML and JavaScript from the jsPsych library [38,39]. The VR condition was coded using the A-Frame library [40]. Separate videos were rendered for the VR and screen conditions, with the screen condition being rendered from a fixed field of view and the VR video rendered in a 360-degree photosphere (see Figure 2). Vimeo was used to host the videos. Participants completed the study on the assigned devices (which they were required to have in their own home per the prescreening survey), using an internet browser to navigate to the task via a URL. For those assigned to the VR condition, a check was performed to detect whether the browser was running on a VR device with connected controllers.

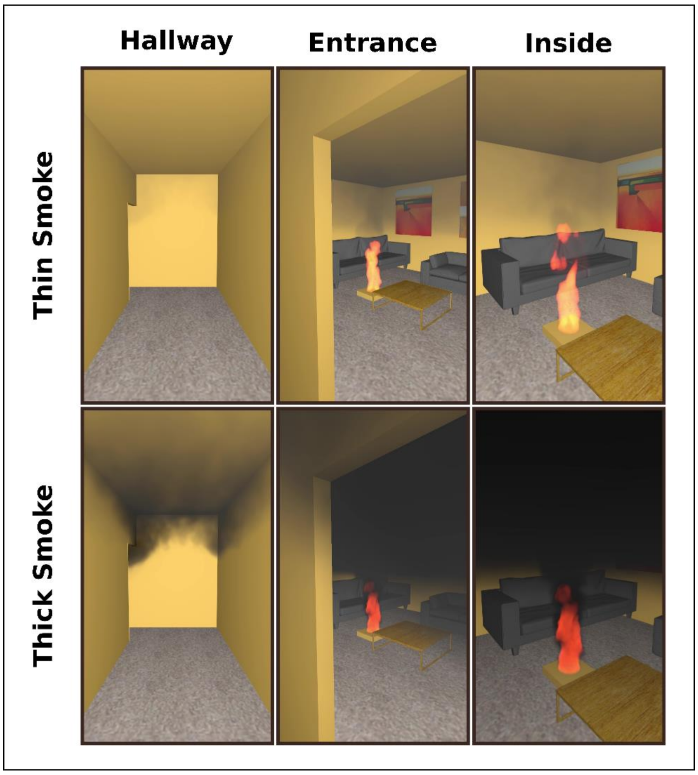

Figure 2. Video frames from each viewpoint location and smoke thickness condition (same growth rate and timestamped at 67 s from the start of the simulation).

Those that were eligible based on the prescreening survey were invited to complete the main experiment, which they carried out from their own home using their own equipment (see Figure 3 for experiment workflow). Prior to the experiment, participants provided informed consent. For the decision-making task, participants in both conditions experienced nearly identical situations, with the main difference being how it was viewed (headset vs. monitor) and interacted with (handheld controllers vs. pointer and keyboard). Participants were first presented with the scenario description via text instructions. They were asked to take the role of an individual staying in a rental detached home as part of a trip. They were informed that they were currently located in their room with their luggage and were watching television. It was explained that at this point, they heard a crackling noise coming from down the hallway near the living room. Following this scenario description, participants were presented with the decision-making task.

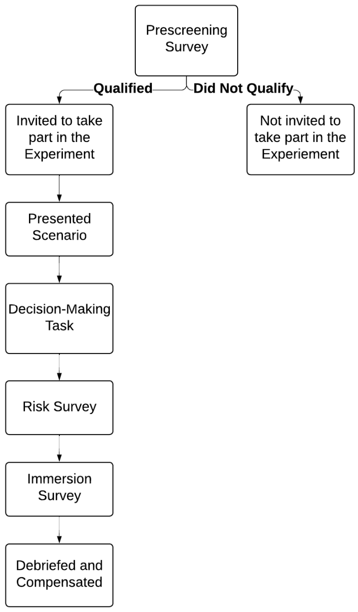

Figure 3. Participant workflow of events undertaken over the course of the study.

For each trial during the task, participants were first given a set of actions they were allowed to take with corresponding descriptions (Table 1). These actions were chosen based on prior research (with consideration of what actions could be performed in the VE) on individual actions taken during fire emergencies [41]. In addition to varying in description, the actions affected the location of the camera within the building: closer to the fire ('Investigate', 'Engage'), farther from the fire ('Gather Belongings', 'Barricade', 'Evacuate'), or no change ('Wait', 'Call 911', 'Continue Watching TV'). In order for the action 'Engage' to be available as a response option, participants must have already selected the 'Investigate' option. After viewing the action descriptions, they were next presented with a video from the corresponding viewpoint within the environment (the initial viewpoint was looking down the hallway toward the living room). To the side of the video was a panel with the available action options (without descriptions). Once the participant selected an action, the video was paused and an inter-trial interval screen was presented, indicating the action was being performed. Prior to the next trial, the action options and viewpoint were updated. Participants were able to make up to five action responses during the course of the decision-making task, with each rendering a new view of the fire.

Table 1. Response options during task and action categories.

Option	Description	Action Category
Investigate	You move forward to take a closer look.	Investigate
Evacuate	You immediately run towards the exit and leave the building.	Protect
Barricade	You return to your room, close the door, and stuff a wet towel under the door.	Protect

Table 1. *Cont.*

Option	Description	Action Category
Continue watching TV	You return to your room and continue watching the television.	Delay
Gather belongings	You look for your stuff and repack your luggage. It takes some time.	Delay
Call 911	You immediately dial 911 using your cellphone. You wait for instructions.	Call 911
Engage	You locate a fire extinguisher and move towards the fire to try to put it out.	Engage
Wait	You stay in your current position, waiting.	Delay

The decision-making task continued in this way until the scenario concluded with the participant either evacuating, barricading themselves, or attempting to extinguish the fire twice. The last option only reached its conclusion if the participant chose to fight the fire twice as the initial attempt to fight the fire resulted in the fire being shown again, indicating that the attempt to extinguish the fire had little effect.

Upon completion of the decision-making task, participants completed a risk survey which contained three questions asking participants to rate the perceived danger of the fire (1 = low, 9 = high; "*What was the severity of the fire*"; "*There was risk of serious harm from the fire*"; "*The fire posed imminent danger*"). Next, participants completed the ARI [30] to rate the level of immersion experienced during the decision-making task. Upon completion, participants were debriefed and provided compensation.

All analyses were conducted in R and JASP with missing data omitted on a pairwise basis. All tests were two-tailed (alpha = 0.05) with familywise error in post hoc tests adjusted using false discovery rate (FDR) corrections. The probabilities of actions occurring initially and transitioning between states were compiled using the 'seqHMM' R package (version 1.2.6) [42]. Ordinal logistic models were fitted by the R package 'ordinal' [43], with effects estimated via the 'emmeans' R package [44]; plots were generated by the 'ggplot2' R package [45]. Using a sensitivity analysis, statistical power of 0.80 for a correlation test with a sample size of 152 participants can be achieved with a minimum effect size of 0.22 (correlation coefficient).

3. Results

3.1. Action Responses

Participants completed up to five actions during the sequence of video simulations. The most frequent initial action was 'investigate' (0.47) followed by 'protect' (0.31), 'call 911' (0.18), and 'delay' (0.04; see Table 2 for transition probabilities). The three most frequently observed actions sequences were 'protect + call 911' followed by 'investigate + engage + engage' and 'investigate + protect + call 911' (see Supplementary Materials for sequence frequencies; Table S1).

Table 2. Transition probabilities from one action (row) to another (column).

From ǀ To	Call 911	Delay	Engage	Investigate	Protect
Call 911	0	0.19	0.21	0.08	0.52
Delay	0.1	0	0.05	0.1	0.75
Engage	0.12	0.02	0.73	0	0.14
Investigate	0.15	0.04	0.51	0	0.31
Protect	1	0	0	0	0

To focus on the impact of fire cues and view on action responses, a multinomial logistic regression analyzed the initial action selected across conditions. The response 'Investigate' was set as the baseline category, with participants selecting 'Delay' as the initial action dropped from analysis due to low response rates (retained N = 152). Significant effects were observed for smoke and view conditions. For thick smoke, 'Protect' and 'Call 911' were more frequently selected compared to thin smoke; z = 4.61, $p < 0.001$, z = 3.23, $p = 0.001$, respectively. For the screen condition, 'Protect' and 'Call 911' were more frequently selected compared to the VR condition; z = 2.14, $p = 0.032$ and z = 2.64, $p = 0.008$, respectively (Figure 4). This supported the hypothesis that the selection of actions taken during the decision-making task would vary by viewing condition and by fire characteristics, specifically smoke.

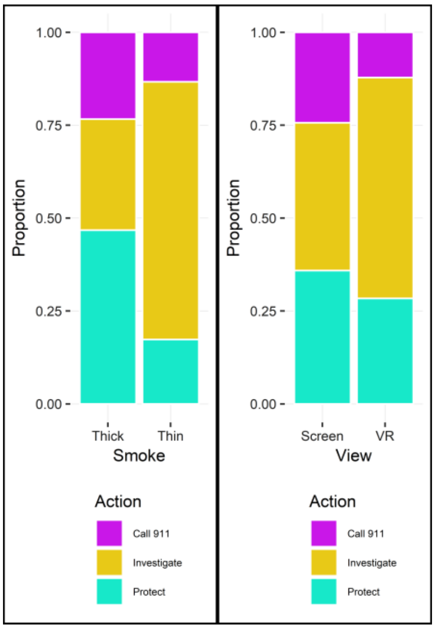

Figure 4. Proportion of first action responses by smoke condition (**left**) and view condition (**right**).

3.2. Risk Ratings

Acceptable interitem reliability was observed across the three risk rating items (Cronbach's alpha = 0.88; risk ratings were missing from 7 participants, retained N = 152). A mixed ordinal logistic regression model (using the 'clmm' function) with main and interaction effects of view, growth rate, and smoke opacity was used to examine whether risk ratings for each item varied by experiment factors (random intercept for participant; factors were dummy coded with baseline levels of screen, thin, and slower). The fitted model revealed a significant main effect of smoke; coefficient = 1.65, standard error = 0.072, z = 2.39, $p = 0.021$ (all other *p*s > 0.2; Figure 5). The main effect of smoke revealed higher ratings for thick than thin smoke. This implies that the main fire characteristic that contributed to the participant feeling the simulated fires posed risk was the thickness of the smoke. This partially supported the hypothesis that participant ratings of risk would vary by fire characteristics.

3.3. Immersion Ratings

Acceptable interitem reliability was observed for each immersion scale (interest = 0.87, emotional attention = 0.77, focus of attention = 0.70, presence = 0.90, flow = 0.70, usability = 0.76). To focus on the immersive aspects of the task, 'usability' was not included in subsequent analyses. Due to evidence of non-normality, non-parametric comparisons were utilized. Using Mann–Whitney U tests, individual item ratings for each scale were compared between VR and screen conditions to identify whether distributions of responses varied by view condition. Significant differences (after adjusting for familywise error) by view condition were observed for the following scales: focus of attention (W = 31,939.00, adj. $p = 0.034$), presence (W = 23,980.50, adj. $p = 0.015$), and flow (W = 31,604.00, adj. $p = 0.047$; all other adj. ps > 0.1; Figure 6). With respect to the screen condition, the distribution of item responses for the VR participants was shifted toward higher immersion ratings for focus of attention and flow scales and toward lower ratings for presence. This provides mixed evidence for the hypothesis that completing the task in VR would contribute to higher immersion.

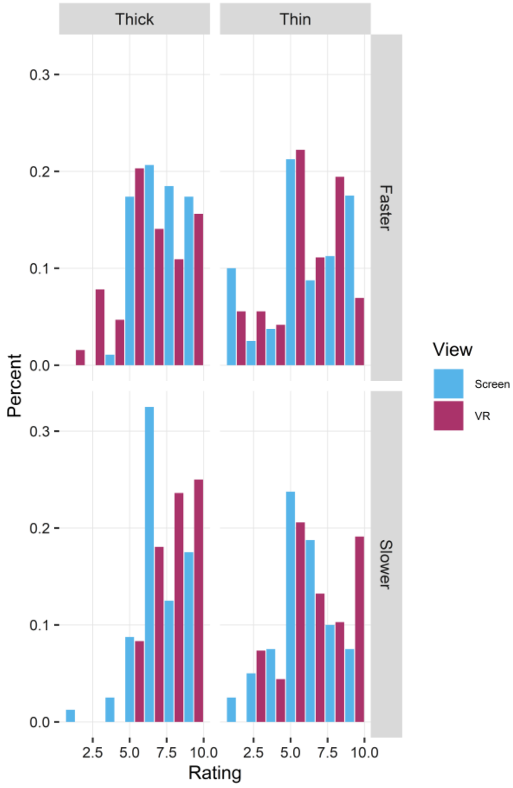

Figure 5. Histograms of risk ratings by smoke (thick, thin), growth (faster, slower), and view conditions. The percent of responses were tallied based on ratings for each risk scale item for each participant.

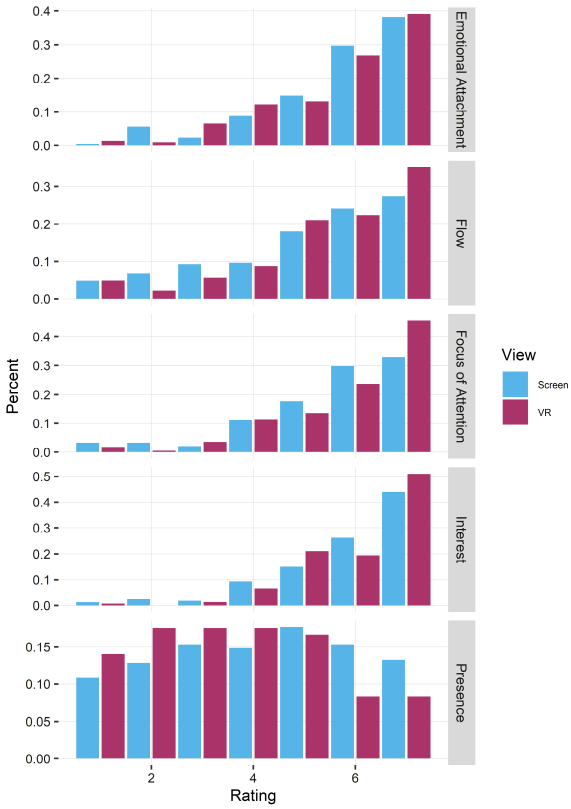

Figure 6. Histograms of immersion ratings by scale and view conditions. The percents of responses were tallied based on ratings for each scale item for each participant.

3.4. Cross-Measure Analysis

Three sets of analyses examined associations between risk, immersion, and action responses. A correlation analysis, using Spearman's rho, with risk and immersion ratings (averaged across items per participant) revealed significant positive associations between risk and interest, rho = 0.226, $p = 0.005$; emotional attachment, rho = 0.198, $p = 0.014$; focus of attention, rho = 0.250, $p = 0.002$; and flow, rho = 0.254, $p = 0.002$, along with significant positive associations between each immersion scale (rhos > 0.3, ps < 0.001). Post hoc statistical power analyses indicated that the achieved power for the significant correlations ranged from 0.70 to 0.90. This was in line with the power sensitivity analysis, suggesting that the sample size was adequate for correlation tests.

Similarly to the initial action analysis, a multinomial logistic regression was used to examine whether risk ratings were associated with selecting 'Protect' or 'Call 911' over 'Investigate'. A significant effect was observed for 'Protect', with greater risk ratings associated with a greater probability of the action being selected, z = 3.02, $p = 0.003$ ('Call 911': z = 1.22, $p = 0.222$; Figure 7).

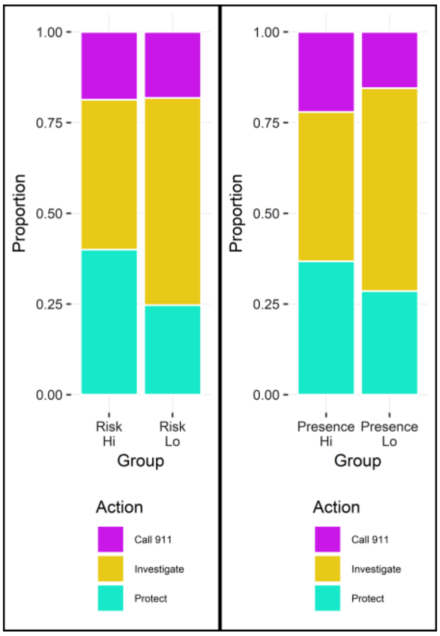

Figure 7. Proportion of first action responses grouped by median split of participant scores ('hi' = greater than median rating) based on risk ratings (left; Med. = 7) and presence ratings (right; Med. = 4).

A separate multinomial logistic regression model, testing whether immersion scales predicted initial actions, revealed greater presence scores were associated with 'Protect' and 'Call 911' actions being more likely to be selected over 'Investigate', z = 2.73, $p = 0.006$, and z = 2.19, $p = 0.029$, respectively (all other p's > 0.08; Figure 7). A follow-up multinomial logistic regression model was used to assess whether both risk ratings and presence scores contributed to initial action selection when entered together as predictors. Both remained significant predictors of 'Protect' (p's < 0.05), and presence was a significant predictor of 'Call 911' ($p = 0.020$) compared to 'Investigate', in the same direction as prior regressions.

4. Discussion

The goal of the present study was to examine whether visual immersion impacted behavior and risk assessment of simulated fires during a hypothetical fire emergency situation. Using numerically generated fire simulations as the VE and presenting them via VR or on a computer screen, participants made a series of action choices, rated the perceived risk of the situation, and reported the immersion they experienced during the task. Our investigation was targeted at discerning whether reactions varied when fires were presented in VR compared to screen formats. We observed evidence that, regardless of the viewing format, the initial actions taken by participants varied by perceived risk and experienced presence.

4.1. Fire Cues Influenced Perceived Risk and Selected Actions

The present study examined the impact of VR and fire characteristics on behavioral responses to a hypothetical fire scenario. We observed partial support for the hypothesis that participant ratings of fire danger would vary by fire characteristics. Significantly higher ratings for thick versus thin smoke were in line with this hypothesis. Risk ratings did not significantly vary by growth rate or by viewing format across conditions. The effect of smoke on perceived risk aligns with prior research based on post-incident surveys [5,6]. Participants in the present study were more likely to take protective action and notify emergency services, compared to investigating the room, with thicker smoke. In field research using post-incident surveys, the amount of smoke spread in a building during fire incidents was observed to be associated with occupant actions [3,4]. Although the actions performed varied, these results replicated the association with smoke within the context of hypothetical fire scenario tasks. These findings also serve to support the idea that, while the fire may not have been photo-realistic, participant behaviors were influenced by the dynamics of the fire presented in the VE.

4.2. The Impact of View Condition on Actions

The initial actions selected by participants varied between screen and VR conditions. Participants in the VR condition chose different initial actions than participants in the screen condition did. Similarly to thin versus thick smoke, participants that viewed the simulation in VR were more likely to investigate the fire rather than take protective action and calling emergency services. Our study used 360-degree photosphere videos, meaning that participants did not have the ability to move around the room, but could rotate their head to view the entirety of the situation [46]. This means that participants in the VR condition had access to more information about the room, visually, at any given time as compared to the screen condition which had a fixed viewpoint. This provides evidence that VR may influence action responses compared to traditional screens during fire scenarios by allowing for more information to be taken in by individuals.

4.3. Immersion Across View Conditions

The present study provides evidence that specific aspects of experienced immersion are affected by presenting a fire scenario via VR. The analysis of immersion ratings revealed a difference in the sense of 'presence', with ratings made by participants in the 'screen' condition shifted higher than those made by participants in the VR condition. Presence referred to the feeling of being surrounded by a blended, yet realistic environment [26]. These analyses indicate that individuals in the VR group felt less of a part of the scenario. Conversely, the ratings of participants of the VR group were higher for 'focus of attention' and 'flow' scales compared to those in the screen group. 'Focus of attention' in this context suggests that participants concentrated on the task more when the VE was presented via VR versus on-screen. 'Flow' refers to an individual's full absorption in the activity: they lose track of time and their thoughts are occupied only by the activity at hand [30]. This indicates that participants in the VR group, while not feeling completely enveloped by the environment, still maintained focus on the activity better and were more absorbed by the simulation.

The relative pattern of effects for presence compared to these other immersion scales for the VR versus screen conditions may have been due to the lack of interactivity. We posit that individuals in the VR condition wanted to explore the environment more than those in the screen condition. Research suggests that VR technology is often sought out by individuals who are sensation seekers (i.e., they look for interesting things to involve themselves with, [47]). Participants in the present study were prescreened such that they reported having prior VR experience and owning VR systems at home. As these participants owned and used a VR headset, they likely had greater experience and exposure to VR games and applications. This, in turn, may have fostered an expectation that the VE should have been navigable and afforded interactions with virtual objects. Indeed, participants in the VR condition were more likely to investigate as their initial action compared to those in the screen condition. Connecting back to the research on immersion in digital media, participants in the VR condition may have been less likely to suspend disbelief compared to those in the screen condition due to the incongruency between the lack of interaction in the task in contrast to prior VR experiences. Overall, this relative effect of VR on aspects of immersion suggests that interactivity may be necessary to suspend disbelief in HBIF simulated fire scenario tasks.

4.4. Impact of Risk and Immersion on Actions

The connections with initial actions taken in the present study emphasize that hypothetical scenarios in HBIF research need to foster feelings of risk and immersion. The levels of perceived risk and immersion were associated with the initial actions taken in the fire scenarios. Correlation analyses of ‘flow’, ‘interest’, ‘emotional attachment’, and ‘focus of attention’ scores indicated individuals who felt more immersed in the environment and simulation felt that the fire was more of a danger. In addition, participants that perceived higher levels of risk were more likely to take protective action. This was also observed with presence scores: the more encapsulated an individual was by the simulation, the more likely they were to select the protective actions over investigating the fire. These findings align with prior research indicating that individuals perceiving fire incidents as more risky take different actions than those perceiving the situation as posing less risk [5,6,15]. Additionally, this further aligns with prior research suggesting that individuals will behave differently when presented with a fire scenario to which they feel more visually immersed within [2]. Overall, these results provide support for the factor of visual immersion being crucial to eliciting behaviors within virtual fire scenarios.

4.5. Limitations and Future Directions

In combination with visual immersion, HBIF studies should investigate the impact of increased interactivity and potential consequences to participants taking part in VE-based tasks. By design, the present study did not examine the impact of user interaction with the scenario presented in the VE. Although participants in both conditions selected actions during the task, they were limited to viewing the videos of the simulated fire. Research indicates that individuals benefit from experiences in which they can move and interact with their surroundings as they are able to use their body to help gain a better understanding of the activity they are trying to accomplish [48]. In line with Arias and colleagues [2], participants may exhibit more realistic behaviors if they are able to interact with the environment in virtual fire scenarios. Future research should examine how the level of interactivity combined with visual immersion impacts behavioral realism in VR. Using the results of the present study for comparison, one possibility is that VR scenarios that have high levels of interactivity may make it more likely that individuals would take protective action as an initial response instead of investigating the environment further. Understanding how visual immersion and interactivity combine to influence behaviors in VEs can better inform how to maximize behavioral realism in lab-based HBIF research.

It is unclear whether the behaviors in more immersed environments are indeed more realistic. The present study suggests that immersion can influence perceived risk and actions in simulated fire decision-making tasks. Prior field-based research has observed that occupants take several different types of initial actions, including those that are associated with protective behaviors, whereas others exhibit investigating behaviors [3]. Thus, without a corresponding real fire incident, it is unclear whether the patterns of actions observed within the screen or VR conditions were more realistic. However, if immersion contributes to realistic behaviors, we predict that the pattern of actions associated with greater presence ratings is more likely to occur in real-world settings. Indeed, when entering both risk and presence ratings as predictors of initial action, higher scores for both measures were associated with protective action over investigative responses. This suggests that if a real-world version of the scenario was implemented, participants may be more likely to take protective action over exploring the building further. Future research should consider how real-world analogs of fire scenarios can be implemented as part of a study to provide comparisons for VR and screen versions of the same task.

5. Conclusions

The present study provides support for enhancing visual immersion as a means of studying people's responses to fire emergency situations. The use of virtual simulations via VR would allow for the study of HBIF without posing risk to individuals and could open new avenues of research that may not have been previously accessible with the methodologies for study in this area. Additionally, the techniques described in this study could help to develop better training programs for fire emergency situations. Prior research has looked at using training programs of this nature [22], and understanding behaviors in these scenarios would only benefit this type of research. This research could benefit building engineers, first responders, and the population in general by allowing a better understanding of how individuals react in fire situations in an effort to be better prepared for the behaviors that come of them. More research is necessary to better understand the connection of VR to behavioral realism so as to extend lab-based findings to real-world situations. Further comparison of these types of simulated fires and real fires of a similar nature could illuminate how these approaches reflect and hopefully mirror the behaviors and reactions of those experienced by individuals in real-fire situations.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fire7120427/s1: Table S1: Frequency of observed action response sequences.

Author Contributions: Conceptualization, M.D.R., J.W.B. and R.R.; methodology, M.D.R., J.W.B. and R.R.; software, J.W.B.; formal analysis, J.W.B. and R.R.; investigation, M.D.R., J.W.B. and R.R.; resources, M.D.R. and J.W.B.; data curation, J.W.B.; writing—original draft preparation, M.D.R., J.W.B. and R.R.; writing—review and editing, M.D.R., J.W.B. and R.R.; visualization, J.W.B. and R.R.; supervision, J.W.B.; project administration, M.D.R. and J.W.B.; funding acquisition, J.W.B. All authors have read and agreed to the published version of the manuscript.

Funding: Research reported in this publication was supported in part by the National Science Foundation under award number 2200416 to J.W.B. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Science Foundation.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Morgan State University (protocol codes 22/05-0107, 22/10-0179).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The study materials and datasets can be found on OSF: https://www.doi.org/10.17605/OSF.IO/3D42R.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. U.S. Fire Administration. Residential Fire Estimate Summaries. Available online: https://www.usfa.fema.gov/statistics/residential-fires/ (accessed on 1 August 2024).
2. Arias, S.; Wahlqvist, J.; Nilsson, D.; Ronchi, E.; Frantzich, H. Pursuing behavioral realism in Virtual Reality for fire evacuation research. *Fire Mater.* **2021**, *45*, 462–472. [CrossRef]
3. Bryan, J.L. *Smoke as a Determinant of Human Behavior in Fire Situations*; U.S. Department of Commerce, National Bureau of Standards: Washington, DC, USA, 1977.

4. Lovreglio, R.; Dillies, E.; Kuligowski, E.; Rahouti, A.; Haghani, M. Exit choice in built environment evacuation combining immersive virtual reality and discrete choice modelling. *Autom. Constr.* **2022**, *141*, 104452. [CrossRef]
5. Kinateder, M.T.; Kuligowski, E.D.; Reneke, P.A.; Peacock, R.D. Risk perception in fire evacuation behavior revisited: Definitions, related concepts, and empirical evidence. *Fire Sci. Rev.* **2015**, *4*, 1. [CrossRef] [PubMed]
6. Menzemer, L.W.; Ronchi, E.; Karsten, M.M.V.; Gwynne, S.; Frederiksen, J. A scoping review and bibliometric analysis of methods for fire evacuation training in buildings. *Fire Saf. J.* **2023**, *136*, 103742. [CrossRef]
7. Sime, J.D. Escape Behaviour in Fires: Panic or Affiliation. Ph.D. Thesis, University of Surrey, Guildford, UK, 1984.
8. Templeton, A.; Nash, C.; Lewis, L.; Gwynne, S.; Spearpoint, M. Information sharing and support among residents in response to fire incidents in high-rise residential buildings. *Int. J. Disaster Risk Reduct.* **2023**, *92*, 103713. [CrossRef]
9. Zhu, R.; Lin, J.; Becerik-Gerber, B.; Li, N. Human-building-emergency interactions and their impact on emergency response performance: A review of the state of the art. *Saf. Sci.* **2020**, *127*, 104691. [CrossRef]
10. Tong, D.; Canter, D. The decision to evacuate: A study of the motivations which contribute to evacuation in the event of fire. *Fire Saf. J.* **1985**, *9*, 257–265. [CrossRef]
11. Lindell, M.K.; Perry, R.W. The protective action decision model: Theoretical modifications and additional evidence. *Risk Anal.* **2012**, *32*, 616–632. [CrossRef]
12. Balog-Way, D.; McComas, K.; Besley, J. The evolving field of risk communication. *Risk Anal.* **2020**, *40*, 2240–2262. [CrossRef]
13. Kuligowski, E.D. Predicting human behavior during fires. *Fire Technol.* **2013**, *49*, 101–120. [CrossRef]
14. Wang, Y.; Kyriakidis, M.; Dang, V.N. Incorporating human factors in emergency evacuation—An overview of behavioral factors and models. *Int. J. Disaster Risk Reduct.* **2021**, *60*, 102254. [CrossRef]
15. Kuligowski, E.D. *The Process of Human Behavior in Fires (NIST TN 1632)*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2009. [CrossRef]
16. Christianson, S.-Å.; Loftus, E.F. Remembering emotional events: The fate of detailed information. *Cogn. Emot.* **1991**, *5*, 81–108. [CrossRef]
17. Nahleen, S.; Strange, D.; Takarangi, M.K. Does emotional or repeated misinformation increase memory distortion for a trauma analogue event? *Psychol. Res.* **2021**, *85*, 2453–2465. [CrossRef] [PubMed]
18. Kensinger, E.A.; Ford, J.H. Retrieval of Emotional Events from Memory. *Annu. Rev. Psychol.* **2020**, *71*, 251–272. [CrossRef]
19. Bonny, J.W.; Leventon, I.T. Measuring human perceptions of developing room fires: The influence of situational and dispositional factors. *Fire Mater.* **2021**, *45*, 451–461. [CrossRef]
20. Bonny, J.W.; Milke, J.A. Precision of Visual Perception of Developing Fires. *Fire* **2023**, *6*, 328. [CrossRef]
21. Hulse, L.M.; Galea, E.R.; Wales, D.; Thompson, O.F.; Siddiqui, A. Recollection of flame height and smoke volume in domestic fires. In Proceedings of the 6th International Symposium on Human Behaviour in Fire, Cambridge, UK, 28–30 September 2015.
22. Morélot, S.; Garrigou, A.; Dedieu, J.; N'Kaoua, B. Virtual reality for fire safety training: Influence of immersion and sense of presence on conceptual and procedural acquisition. *Comput. Educ.* **2021**, *166*, 104145. [CrossRef]
23. Ahmadi, M.; Yousefi, S.; Ahmadi, A. Exploring the Most Effective Feedback System for Training People in Earthquake Emergency Preparedness Using Immersive Virtual Reality Serious Games. *Int. J. Disaster Risk Reduct.* **2024**, *110*, 104630. [CrossRef]
24. Gagliardi, E.; Bernardini, G.; Quagliarini, E.; Schumacher, M.; Calvaresi, D. Characterization and future perspectives of Virtual Reality Evacuation Drills for safe built environments: A Systematic Literature Review. *Saf. Sci.* **2023**, *163*, 106141. [CrossRef]
25. Scorgie, D.; Feng, Z.; Paes, D.; Parisi, F.; Yiu, T.W.; Lovreglio, R. Virtual reality for safety training: A systematic literature review and meta-analysis. *Saf. Sci.* **2024**, *171*, 106372. [CrossRef]
26. Breuer, C.; Loh, K.; Leist, L.; Fremerey, S.; Raake, A.; Klatte, M.; Fels, J. Examining the auditory selective attention switch in a child-suited virtual reality classroom Environment. *Int. J. Environ. Res. Public* **2022**, *19*, 16569. [CrossRef] [PubMed]
27. Vince, J. *Introduction to Virtual Reality*; Springer Science & Business Media: London, UK, 2011.
28. Lovreglio, R.; Duan, X.; Rahouti, A.; Phipps, R.; Nilsson, D. Comparing the effectiveness of fire extinguisher virtual reality and video training. *Virtual Real.* **2021**, *25*, 133–145. [CrossRef]
29. Shaw, E.; Roper, T.; Nilsson, T.; Lawson, G.; Cobb, S.V.G.; Miller, D. The heat is on: Exploring user behaviour in a multisensory virtual environment for fire evacuation. In Proceedings of the Conference on Human Factors in Computing Systems, Glasgow, UK, 4–9 May 2019. [CrossRef]
30. Georgiou, Y.; Kyza, E.A. The development and validation of the ARI questionnaire: An instrument for measuring immersion in location-based augmented reality settings. *Int. J. Hum.-Comput. Stud.* **2017**, *98*, 24–37. [CrossRef]
31. Tekinbas, K.S.; Zimmerman, E. *Rules of Play: Game Design Fundamentals*; MIT Press: Cambridge, MA, USA, 2003.
32. Simeone, A.L.; Cools, R.; Depuydt, S.; Gomes, J.M.; Goris, P.; Grocott, J.; Esteves, A.; Gerling, K. Immersive speculative enactments: Bringing future scenarios and technology to life using virtual reality. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, New Orleans, LA, USA, 29 April–5 May 2022.
33. *Fire Dynamics Simulator (FDS6.7.9) [Computer Software]*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2022. Available online: https://github.com/firemodels/fds.
34. PyroSim. [Computer Software]. Thunderhead Eng. 2022. Available online: https://www.thunderheadeng.com/pyrosim.
35. Forney, G.P. *Technical Reference Guide (NIST Special Publication 1017-2; Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data)*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2023.

36. Bonny, J.W.; Hussain, Z.; Russell, M.D.; Trouvé, A.; Milke, J.A. Simulated fire video collection for advancing understanding of human behavior in building fires. *Front. Psychol.* **2024**, *15*, 1438020. [CrossRef]
37. Kim, H.-J.; Lilley, D.G. Heat release rates of burning items in fires. *J. Propuls. Power* **2002**, *18*, 866–870. [CrossRef]
38. Lange, K.; Kühn, S.; Filevich, E. "Just another tool for online studies" (JATOS): An easy solution for setup and management of web servers supporting online studies. *PLoS ONE* **2015**, *10*, e0130834. [CrossRef]
39. de Leeuw, J.R. jsPsych: A JavaScript library for creating behavioral experiments in a web browser. *Behav. Res.* **2015**, *47*, 1–12. [CrossRef]
40. A-Frame. [Computer Software]. 2024. Available online: https://github.com/aframevr/aframe.
41. Arias, S.; Nilsson, D.; Wahlqvist, J. A virtual reality study of behavioral sequences in residential fires. *Fire Saf. J.* **2021**, *120*, 103067. [CrossRef]
42. Helske, S.; Helske, J. Mixture Hidden Markov Models for Sequence Data: The seqHMM Package in R. *J. Stat. Softw.* **2019**, *88*, 1–32. [CrossRef]
43. Christensen, R.H.B. ordinal—Regression Models for Ordinal Data. 2023. Available online: https://CRAN.R-project.org/package=ordinal (accessed on 1 August 2024).
44. Lenth, R.V.; Buerkner, P.; Herve, M.; Love, J.; Miguez, F.; Riebl, H.; Singmann, H. emmeans: Estimated Marginal Means, Aka Least-Squares Means (Version 1.7.3). [Computer Software]. 2022. Available online: https://CRAN.R-project.org/package=emmeans.
45. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2016.
46. Feng, Z.; Liu, C.; González, V.A.; Lovreglio, R.; Nilsson, D. Prototyping an immersive virtual reality training system for urban-scale evacuation using 360-degree panoramas. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1101*, 022037. [CrossRef]
47. Vishwakarma, P.; Mukherjee, S.; Datta, B. Travelers' intention to adopt virtual reality: A consumer value perspective. *J. Destin. Mark. Manag.* **2020**, *17*, 100456. [CrossRef]
48. Grade, S.; Badets, A.; Pesenti, M. Influence of finger and mouth action observation on random number generation: An instance of embodied cognition for abstract concepts. *Psychol. Res.* **2017**, *81*, 538–548. [CrossRef] [PubMed]