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The effects of information and hazard on evacuee behavior in virtual reality

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ABSTRACT

Many contextual factors can influence evacuees' choice of egress route during an emergency. Anxiety caused by the emergency situation may lead to suboptimal choices, resulting in slower evacuation and greater risk of injury or death. The present pilot study tests the influence of hazard level (presence of visible fire and smoke) and information about an obstacle (delivered verbally or through signage) on evacuees' anxiety levels and choice of egress route in a virtual reality (VR) simulation of a fire evacuation with multiple possible exits. Physiological measures were recorded and used to validate the efficacy of VR in inducing anxiety germane to the situation of interest. Consistent with our expectations, providing information about the obstacle was shown to decrease total evacuation time. Contrary to our predictions, it did not significantly impact evacuees' choice of exit. Information also had a marginally significant effect on participants' self-reported anxiety. Providing more targeted information may further reduce anxiety and evacuation time. More generally, VR appears well-suited to assessing individual and psychological factors in evacuations.

1. Introduction

1.1. Issues in evacuation

Various considerations may impinge on an evacuee's choice of exit and egress route: familiarity with the available exits of the building, the choices made by other evacuees, the information provided by emergency officials or by building signage, and more. These factors frequently converge in ways which produce sub-optimal exit choices and egress routes, thereby increasing the time required to exit the building and the likelihood of not escaping safely [1]. Our aim in this pilot study is to use physiological and self-report measures to extend past research establishing the utility of Virtual Reality (VR) as a testbed to study issues in evacuation, and further to identify particular environmental and social factors which influence evacuees' choices and develop methods of improving efficiency in evacuations.

Detailed case studies provide a starting point for addressing common problems preventing safe and efficient evacuation during emergencies [3,8,10,25,41,42]. In one tragic case, evacuees fleeing a fire at the Station Night Club in West Warwick, Rhode Island headed towards the main doors of the building while ignoring available peripheral exits [1]. Overcrowding at the main doors significantly slowed movement, contributing to several dozen fatalities. [1] note that, in this case, evacuee density and death rate were highly correlated. Evacuee behavior of this kind during fire emergencies has historically been explained with reference to panic; untested "truisms" paint evacuees as an unthinking herd [41]. However, such assumptions about evacuee behavior have largely been discredited [18,32,33,35,41]. As such, modern evacuation research tends to forgo the panic explanation and approach crowd dynamics with greater nuance, addressing evacuee decision-making and associated social, physical, and situational factors [9].

Overcrowding at exits is theorized to result from the confluence of several problems. For individual evacuees, anxiety caused by the emergency situation may result in adverse effects, given the conditions faced. While anxiety due to a perceived emergency can motivate action [39], excessive physiological arousal will reduce performance [47]. This effect has been demonstrated in emergency evacuations, where evacuees tend to take longer in making decisions and make sub-optimal choices while under stress [4]. Furthermore, prior research indicates that the breadth of attention is reduced during high-anxiety situations, resulting in decreased salience of potentially important information – a phenomena known as attentional narrowing [6,48]. In the case of a fire emergency, high levels of anxiety may cause such attentional narrowing. Attentional narrowing could in turn cause evacuees to ignore signage or other

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information indicating alternative, less crowded exits and head for the main exit, with which they are likely to be most familiar and therefore have a propensity to use, even in non-emergency situations [42]. As a result of individual evacuees' anxiety-influenced actions, the main or familiar exits would become more crowded, and that crowding may, in turn, further increase anxiety. A combination of anxiety and crowding at main exits may increase competitive behavior, such as pushing, resulting in blocking of exits or narrow passageways and producing a faster-is-slower effect [7,26,43]. These phenomena are highly interrelated [19]; explain that impatience leading to faster movement can increase time to exit due to the associated increase in crowding – hence faster-is-slower.

Additionally, building occupants may take the exit choices of their fellow evacuees as informative of which exits are safe for use. [23,24] found that the social influence of one person evacuating with the participant affected participant route choice, but not destination choice. Theoretically, a larger group of individuals should exert greater social influence [27] and thus might affect destination or exit choice. [13] contends that the perception of affordances, or opportunities for action, in a given environment is contingent in part on a person's social identity and the social, intentional, and institutional aspects of the environment. When all building occupants have a shared intention to evacuate and a large number of those occupants head for one exit, it indicates to the members of the group that particular exit affords egress and safety, to the exclusion of other exits. Applying the affordance-based approach explicated by Ref. [13] and others in the Gibsonian tradition [16,38] enables the explanation or reconceptualization of this kind of behavior as the rational use of relevant, albeit incomplete or inaccurate, information, rather than the product of group-think or a “herd mentality”. An affordance-based interpretation fits neatly with other modern approaches to understanding evacuee behavior which eschew a panic-based framework [1]. From a more practical standpoint, understanding and altering affordances of various types may improve evacuation efficiency. Indeed [37], were able to increase emergency exit utilization in a virtual evacuation by manipulating the affordances of the environment. Conversely, and more similar to the current study [30], applied the theory of affordances to evaluate signage which dissuaded participants from utilizing a particular exit in a virtual evacuation.

We suggest that evacuees' anxiety could be reduced by judicious deployment of well-tested, task-relevant information. Anxiety is theorized to result, in part, from evacuees' inability to exit at their desired rate or the expectation that they will not be able to do so. In the current pilot study, an obstacle (a low table) was placed near the main exit of a building during a virtual fire evacuation (see section 1.2), creating a bottleneck with reduced capacity and increased crowding. However, the obstacle was not initially visible to the participant due to its being occluded by the presence of several dozen computer-controlled avatars evacuating alongside the participant. Information provided to the participant was intended to reduce anxiety or irritation by resolving the ambiguity created by this occlusion regarding the cause of this otherwise unreasonable slowing of crowd movement. Information was provided by either a hanging sign indicating the table's presence, or a pre-recorded spoken message directed at the participant from one of the avatars, and will offer an explanation for slowing and crowding at the main exit – namely, that an obstacle is present and inhibiting egress. Reduced anxiety should, in turn, result in less attentional narrowing and competitive behavior, potentially attenuating the faster-is-slower effect and decreasing overall time to exit for the evacuee. Additionally, utilization of peripheral exits could be increased, influencing the loading of the available exit capacity. If this is found to be the case, it implies important real-world consequences. Namely, groups of evacuees with reduced anxiety will engage in less competitive behavior, attenuating the faster-is-slower effect. If their use of peripheral exits is increased, resulting in better utilization of the available exit capacity, it would further attenuate anxiety caused by crowding and reduce the total time required to evacuate a building. This would be especially true when peripheral exits are closer than main exits to many evacuees, as is often the case in large buildings. Decreasing the time required to evacuate a building should ultimately decrease the number of injuries and fatalities.

1.2. Virtual reality and methodological issues

Attempting to study the factors influencing evacuation behavior poses several methodological and ethical issues. Much of the existing literature on emergency evacuations comes from case studies of attention-grabbing events such as the Station Night Club fire, or the World Trade Center evacuations on September 11, 2001 [1,3,11, 50]. Case studies provide valuable insights into matters such as exit preference and evacuation initiation delay, but do not allow for the manipulation of key variables, and therefore offer little help in developing conceptual models or methods to increase evacuation efficiency. Computer models, capable of approximating evacuee movements during evacuations, are useful in understanding the influence of building layout, especially as it pertains to crowding and competitive behavior [21,31,49]. However, they do not faithfully incorporate psychological factors such as anxiety and attention which are key to understanding evacuee behavior. The limitations of case studies and computer modeling might be overcome through large-scale experiments approximating actual evacuations [20]. However, validating the ability of such experiments to replicate a real emergency with sufficient veracity to induce anxiety in the participants is difficult, limiting their ability to provide actionable information. In spite of these challenges, researchers have noted a critical need for social psychological experiments that “conduct tests under controlled circumstances … quantifying by formulating verifiable theories” [25].

As such, many have turned to VR to simulate emergency evacuations under controlled conditions. VR has proven useful in safely replicating high-anxiety situations for a variety of purposes, included Post-Traumatic Stress Disorder therapy [34], treatment of phobias [28,29], and fire-fighter training [44]. [23,24] have outlined several strengths and weaknesses of using VR in fire evacuation research. Namely, VR enables a unique combination of realism and control in emergency evacuation scenarios. In VR we can manipulate the circumstances of evacuation and collect fine-grained data on evacuee behavior. However, VR is only as useful as its ability to model the situation of interest and engender an appropriate response in participants. [23,24] state that “high – but not absolute – ecological validity of VR studies can be assumed if the visualization, observed behavior, and task difficulty of a simulated fire emergency is realistic …” VR simulations vary in their ability to capture many physical (sensation of heat, smell of smoke) and social (presence of friends and family, communication among evacuees) aspects of a fire evacuation. Additionally, the unfamiliar nature of VR interaction may result in behaviors unlike those exhibited in real evacuations. Despite this [15], note that participants respond adaptively to fire emergencies in virtual environments, seeking exits and hurrying in response to a sudden and unexpected fire emergency. The current pilot study expands on this and similar work to examine the efficacy of VR in convincingly replicating the circumstances of a real fire evacuation.

As previously indicated, anxiety and its resultant behavioral effects are hypothesized to produce or contribute to many problems in emergency evacuations. VR scenarios capable of inducing anxiety provide an avenue to assess methods of reducing that anxiety, and ultimately improving real life evacuation efficiency. Several prior studies have employed survey measures in order to assess anxiety caused by VR scenarios [23,24,29], indicating that self-reported anxiety can indeed be manipulated by VR. The current study includes survey measures, but adds physiological measures similar to those of [28]; who found that the heart rates of tunnel-phobic participants increased significantly when moving through a tunnel simulated in VR. The application of such measures in a VR fire evacuation context is, to the best of our knowledge, unique. Here, unlike [28]; physiological measures will be used to assess the responses of non-phobic participants to a universally stressful and hazardous scenario. Although the stakes involved in an evacuation are necessarily lower in VR, and therefore participant investment lesser, it is important for VR to provide a high level of psychological realism. If it is the case that VR is sufficient to produce anxiety in participants during simulated emergencies, we may assume that a similar scenario in real life would produce much *greater* levels of anxiety. However, the physiological measures currently employed allows us to specifically assess moment-to-moment increases in anxiety, indicating a startle response, which may be caused by specific events in VR and are interpretable separate from the overall level of anxiety experienced [28]. These real-time responses to specific incidents in VR, rather than the overall self-reported level of anxiety, are of primary interest. It should be noted that, due to a variety of differences between VR and real evacuations, VR research cannot and should not supplant other methods. Research involving real emergencies, if possible, is an important next step, and any effects observed here are expected to be relatively muted by comparison. However, validation studies can elucidate which factors affecting evacuations may be adequately addressed in VR and indicate directions for future research.

1.3. The current study

To maximize realism, evacuation scenarios for the current pilot study were developed in a highly detailed VR recreation of the Homer Babbidge Library (Fig. 1), a fixture of the University of Connecticut Storrs campus. Individual participants engaged in a series of VR scenes culminating in an evacuation of the library in which the participant evacuated alongside several dozen computer-controlled avatars. The library has clearly differentiated main and peripheral exits (Fig. 1) – an important feature for testing hypotheses regarding exit choice. Main exits are centrally located, and used almost exclusively by students and other library visitors in real life. Peripheral exits are located nearer the building's perimeter, and are seldom used.[1] In the VR simulation, a low table was placed in the middle of the path leading from the participant's starting location to the library floor's main exit, creating crowding and increasing time to exit by restricting capacity (Fig. 1). In this scene, the hazard level of the evacuation was manipulated, with some participants seeing simulated fire and smoke during their evacuation, and some seeing neither fire nor smoke (Fig. 2). Additionally, the information available to participants regarding the obstacle inhibiting egress was manipulated. Some participants received no information about the obstacle's presence, while other participants received information alerting them to it by way of signage or pre-recorded dialogue (Fig. 3). The information provided was intended to reduce participants' anxiety by providing an explanation for the crowding near the main exits. We hypothesized that participants in the high hazard (fire and smoke visible) condition would experience more anxiety and take longer to reach an exit than participants in the low hazard (no fire or smoke) condition, unless information was provided to reduce their level of anxiety. Although perception of high hazard by itself should encourage participants to attempt to move more quickly [51], we expected the benefit of increased speed would be negated by other consequences of the increased anxiety caused by the high hazard, namely, sub-optimal exit choice and increased competitive behavior. This is particularly the case because the participants' speed was naturally limited by the presence of the computer-controlled avatars, especially where they were densely packed, as was the case near the obstacle and main exits. Due to limitations of the VR simulation and control method (see 2.4 & 4.2), movement speed was not measured directly. Participant behavior was instead measured by exit choice and time to reach an exit. Anxiety was measured by survey questions after completing the VR portion of the experiment, as well as ongoing measurement of heart rate (HR) and galvanic skin response (GSR) at key moments during VR scenes. Survey items indicated general anxiety about the experience, while more fine-grained physiological information was used to glean sudden increases in HR and GSR, indicating surprise or increased anxiety. HR and GSR have been demonstrated as appropriate measures of anxiety in VR [12,28,45], though their use here as tools for assessing VR for fire evacuation research is novel. We also predicted that participants provided with information about the obstacle would not only experience relatively less anxiety, but also favor peripheral exits, display less competitive behavior, and take less time to evacuate than participants who received no such information. Finally, we sought to validate the utility of VR in studying emergency evacuation behavior using the above-mentioned survey data and physiological measures of participant anxiety. If our circumstances affect anxiety as predicted despite the upper limitations on anxiety provided by participants' awareness that the emergency is not real, it provides a compelling case that VR can be useful for examining real-world anxiety-inducing evacuations.

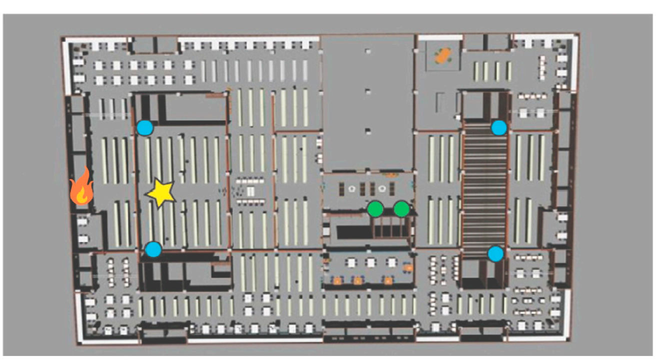

Fig. 1. Layout of Homer Babbidge Library 3rd Floor. Participant starting location marked by yellow star. Main exits marked by green dots. Peripheral exits marked by blue dots, with nearby exists on the left and distant exits on the right. Location of fire (in High Hazard condition only) marked by flame symbol. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

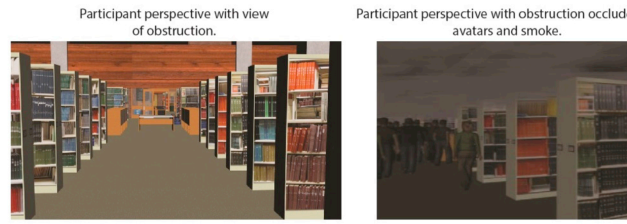

Fig. 2. Participant views in Low Hazard and High Hazard conditions. Avatars absent in image for Low Hazard condition to show location of obstruction.

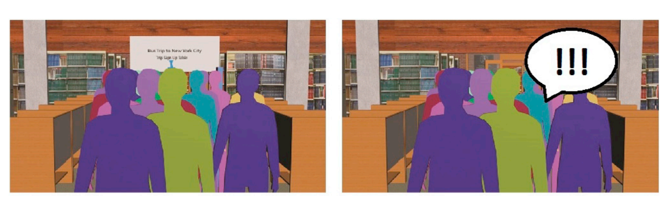

Fig. 3. Representations of Signage (Left) and Verbal (Right) Information conditions. Avatars (depicted as silhouettes) occlude obstacle in both conditions.

[1] We operate under the assumption, corroborated by self-report measures presented in Section 3.2, that participants, being UConn students, have high familiarity with the library setting. Participants would have had repeated exposure to signage pointing out peripheral exits. Students rarely use them, however: the exits allow travel between floors, but do not allow egress from the library except in an emergency (they are alarmed at the exit).

2. Materials and methods

2.1. Design

Participants were randomly assigned to one of six conditions in a 2 (Hazard) x 3 (Information) between-subjects design. Participants saw either fire and smoke in the evacuation scenario (High Hazard), or no fire and smoke (Low Hazard). Additionally, participants received either no information, information via signage, or verbal information about an obstruction slowing their evacuation. The VR portion of the experiment was composed of three scenes: a training scene in an unfamiliar room, a manipulation-check scene on the first floor of the library, and the experimental scene on the third floor of the library (Fig. 4). Manipulations were only introduced during the final scene of the multi-part VR portion of the experiment, described in detail in section 2.5.

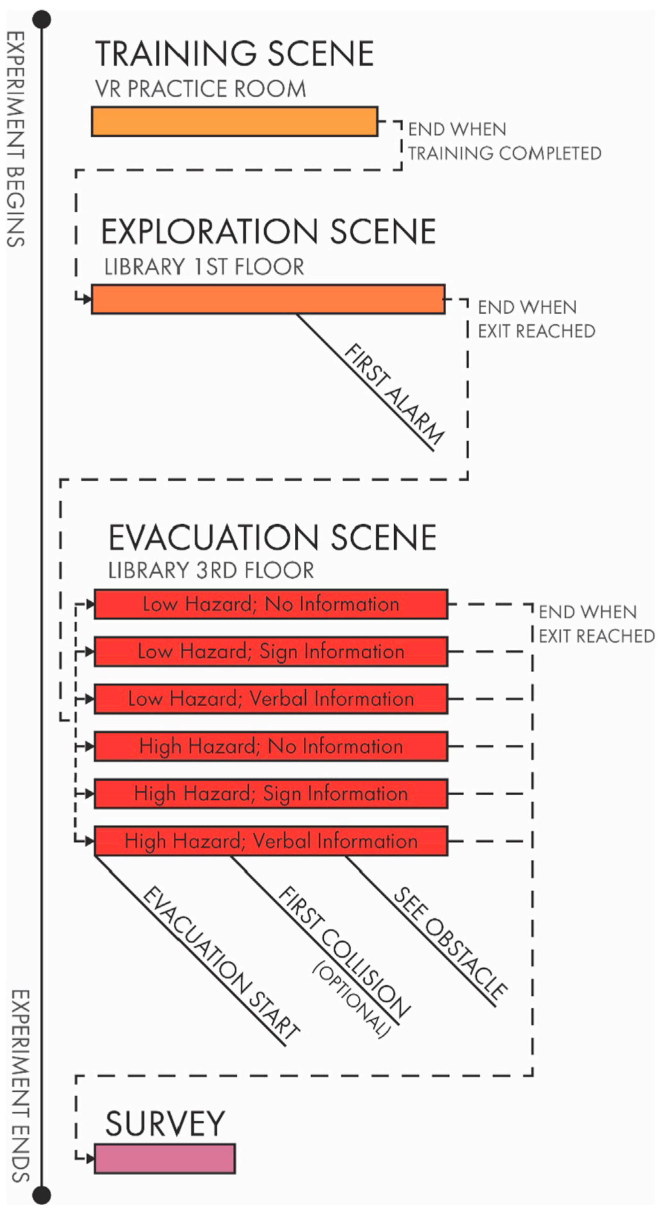

Fig. 4. Timeline of experiment. The training scene, exploration scene, and evacuation scene took place in VR. Participants were randomly assigned to one of six versions of the evacuation scene; all other scenes were identical for all participants. VR events used for analysis of physiological data are marked "FIRST ALARM", "EVACUATION START", "FIRST COLLISION", and "SEE OBSTACLE". Physiological data were collected for all versions of the evacuation scene.

2.2. Dependent variables

HR and GSR data were collected for the duration of the VR portion of the experiment. From these data, slices surrounding key moments were extracted for analysis. In the second scene (on the first floor of the library), HR and GSR data were extracted before and after the fire alarm activated. In the third scene (on the third floor of the library), HR and GSR data were extracted before and after the start of the scene, the participants' first collision with another avatar, and their first time spotting the obstacle impeding their evacuation. In all cases, data were from a one second window immediately preceding the event of interest, and a six second window starting three seconds after the event of interest. HR and GSR means for each of these data extraction windows were calculated. Maximum HR and GSR levels during each window were also recorded. Data collection windows were selected to maximize our ability to capture physiological changes owing to the events of interest.

All information concerning exit choice and time to exit was obtained from summary data extracted from VR. Competitive behavior was similarly operationalized as the number of collisions made with computer-controlled avatars as recorded by the VR software. There was no threshold number of collisions used to categorize participants' behavior as competitive or non-competitive; doing so would have decreased the power of subsequent analyses by discretizing a continuous variable. A survey was generated to collect data on familiarity with the Homer Babbidge Library, self-report measures of anxiety, and perceived realism of the VR scenario and the avatars' behavior (see Fig. 5).

2.3. Sample

Thirty-nine participants were recruited from undergraduate psychology classes. Two participants dropped out during the experiment due to VR-related motion sickness. The sample was further narrowed to include only those participants who produced reliable physiological readings, excluding those who had abnormal HR or GSR levels, or whose data contained irregularities likely due to excessive movement during VR or poor contact of physiological sensors with their skin. Of the twenty-seven participants constituting the final sample, nineteen were female and eight were male. Of those same twenty-seven, 66% were Caucasian, 15% were African American, 11% were Hispanic American, 7% were Asian American, 4% were Native American, and 7% reported their race as Other. Percentages add to more than one hundred due to some participants selecting more than one option, i.e. Caucasian and Hispanic American. The average age of participants was 19.11 years old, with a standard deviation of 1.13. All participants had normal or corrected to normal vision. Participants were assumed to have limited prior experience with VR. Participants were compensated for their time with class credit.

2.4. Apparatus

A Sony HMZ-T1 Virtual Reality system was used to present the virtual evacuation scenarios. Throughout the VR portion of the experiment, participants wore the HMZ-T1 head mounted display and controlled their movement with a track-ball mouse and Polhemus motion-tracking system to provide an immersive experience. Participants navigated the virtual environment by rolling the mouse's track-ball with the fingertips of their dominant hand, generating step-like movements; participants simply pushed the trackball forward to step forward. Continuous movement was achieved by continually rolling the track-ball forward by pushing it with the fingertips. Movement speed was determined as a function of track-ball speed and scaled to the virtual environment; there was no hard limit on the participants' movement speed, as this method is naturally self-limiting. Additionally, movement speed was not additive, so the participant's avatar slowed as the track-ball slowed. The head mounted display offered a resolution of 1280×720 (per eye), with a 45° horizontal field of view and 51.6° vertical field of view. The paths of

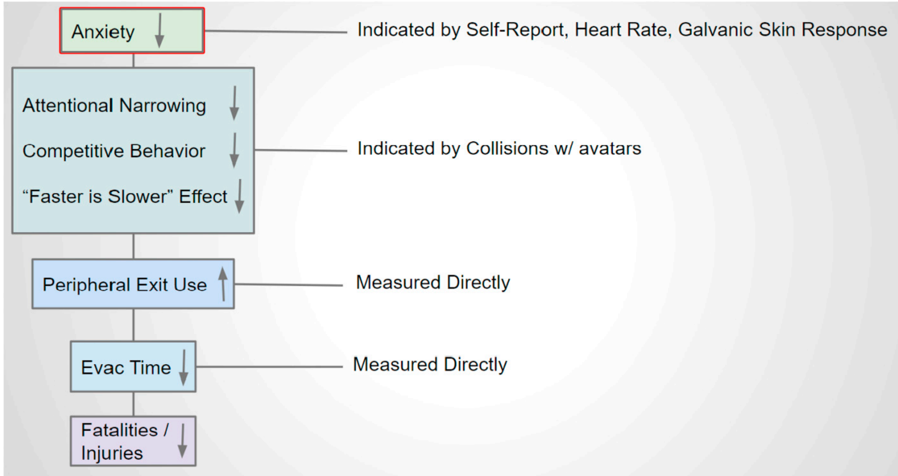

Fig. 5. Anticipated relationships between constructs and phenomena of interest, and their relationship to dependent variables in the current study. Arrows indicate expected direction of influence, i.e. decreased anxiety would be associated with decreased competitive behavior and increased peripheral exit use.

computer-controlled avatars during evacuation scenes were determined by models developed using the open-source Fire Dynamic Simulation + Evacuation (FDS + Evac ver 2.3.1) software package. Avatar exit choice was controlled via the familiarity parameter, such that avatars had a 100% chance of being familiar with main exists, an 80% chance of being familiar with distant peripheral exits, and a 10% chance of being familiar with nearby peripheral exits (see Fig. 1 for exit locations). As such, the majority of avatars moved towards the main exits. Avatars which selected distant peripheral exits for use moved through the bottleneck near the main exits, and therefore contributed to the crowding near main exits. Paths were extracted from FDS + Evac and applied to computer-controlled avatars in the VR environment, which was built with WorldViz Vizard (ver 4.0). Avatars followed their predetermined paths unless blocked, in which case they would cease movement until the blockage was removed. The social force model from FDS + Evac was not implemented between the participant and avatars in VR. While avatars affected each other's trajectories in the FDS + Evac simulation, the participant could not push the avatars, or vice versa, during VR. The VR software recorded participants' evacuation times and exit choices while simultaneously marking key events, such as a fire alarm triggering, or a collision with a computer-controlled avatar occurring. Physiological measures were collected using a Biopac MP-150 system recording into AcqKnowledge (BIOPAC Systems, Inc.) running on a separate computer. Heart Rate measurements were obtained with two pre-gelled disposable electrodes (BIOPAC Systems EL503) attached at the upper right and lower left chest. Galvanic Skin Response measurement were obtained with two pre-gelled disposable electrodes (BIOPAC Systems EL507) attached to the distal phalanges of the index and middle fingers of the non-dominant hand. Key events in the simulation were marked by the VR software in the physiological data via parallel port connection. Survey materials were administered with Empirisoft MediaLab.

2.5. Procedure

Participants were first provided with an informed consent form on which they indicated their awareness and acceptance of all experimental procedures. Deception was involved, as participants initially believed that they were participating in a study only concerned with aesthetic evaluation of virtual environments. They were then accompanied to a small, quiet room, intended to minimize outside influence on the VR experience, for participation in the experiment. Participants were instructed on proper procedure for attaching heart rate (HR) and galvanic skin response (GSR) sensors, which they applied themselves to minimize experimenter contact. After attaching sensors for physiological data, the participants were instructed to put on the VR headset. An experimenter provided guidance in adjusting the headset for optimal fit and clarity of vision. After confirming that all apparatus were properly in place and functioning, an experimenter initiated the VR portion of the experiment. Participants were again informed that they could drop out of the experiment at any time with no consequences if they began to experience motion sickness, or for any other reason.

The VR portion of the experiment was divided into three discrete scenes, each separated by a brief pause and black screen. A timeline of VR scenes is given in Fig. 4. The first was a training scene, in which participants were provided with basic instruction on movement and interaction in VR. The scene took place in a small, sparsely decorated room with a single computer-controlled avatar providing verbal instruction. Participants were able to use this scene to acclimate themselves to virtual reality. This introductory scene did not vary between participants. During the scene participants were guided through a series of simple tasks which involved moving and looking in order to ensure their competency in using VR. The training scene ended only after all tasks had been successfully completed.

In the second scene, participants were required to explore the large, unpopulated first floor of the Homer Babbidge Library, a familiar feature of the UConn Storrs campus recreated in VR. Participants indicated that they were aware that the VR setting was the library (see 3.2). The floor of the library used in this scene, along with that used in the next scene, featured two main exits (adjacent to each other), and four peripheral exits, each near a corner of the floor (see Fig. 1). Participants were initially instructed to explore the entire library floor, consisting of several large open areas as well as smaller rooms, in order to get a feel for its layout. The scenario kept track of when the participant entered several key locations. Once all of these locations had been visited in any order, a fire alarm sounded. If the participant had still not visited all locations by a fixed time, the fire alarm sounded anyway. This was the first indication of any kind of the experiment's true intent; up this point no mention of evacuation was made, and no indication was given that an evacuation might take place. The fire alarm sound employed here and in the third scene was recorded from the alarm system in the Homer Babbidge Library, and featured a klaxon-like sound along with verbal instruction to evacuate the building by the nearest exit. The scene ended when the participant reached any one of the exits of the floor. This scene was developed in order to establish baseline levels for participant heart rate and galvanic skin response, further acclimate participants to the use of VR, and establish participant responsiveness to stressful events in VR (i.e., the fire alarm). When the fire alarm activated in this scene, it also automatically created a marker in the physiological data in order to enable analysis of changes in HR and GSR due to the startling alarm. This marker is referred to as "First Alarm" in section 3.1.

In the third and final scene, also set in the Homer Babbidge Library, all participants were first instructed by text on a black screen to evacuate from the library. This screen was included to indicate to participants that they were being placed in a new situation, avoiding any implied continuity, and associated confusion, between the two consecutive scenes taking place in the library. At the opening of the scene participants were placed on the third floor of the library, a good distance from the main exits of that floor, with fire alarms already active and instructing them to leave by the nearest exit. Participants began the scene facing away from the main exits and pointed toward an area where, if they were in the High Hazard condition, there was clearly visible fire and smoke visually represented with particle systems. Visual representation of smoke in the VR simulation was intended to approximate smoke present in the FDS + Evac simulation (See Appendix A for FDS + Evac parameters). However, concessions were made so as to not obstruct participants' vision. The smoke was included only to increase the perceived hazard of the situation, and thereby anxiety, and not to simulate specific impacts of smoke on visibility. As such, smoke never became so dense that participants could not see the sign (in the Information condition), the other evacuees, or their way forward. At the start of this scene a second marker was added to the physiological data, labelled "Evacuation Start" in section 3.1, in order to assess increased anxiety due to the sudden introduction of a novel, hazardous scenario, and differences in the increase in anxiety owing to the presence or absence of fire and smoke. Participants were required to locate and reach an exit to end the scene. Several dozen computer-controlled avatars were also present in this scene, evacuating alongside the participant. In order to imitate typical evacuee behavior, the computer-controlled avatars primarily made use of the floor's main exits, though several also made use of peripheral exits. The trajectories of computer-controlled avatars were held constant between experimental conditions. Allowing fire and smoke to affect avatar trajectories may have provided greater "mundane realism" defined as a good match to what occurs in the real world [2], as real evacuees would reasonably be expected to behave differently in their presence. However, this concession would have introduced a confounding variable. The path to the main exit of the floor in this scene was obstructed by a table, creating a bottleneck through which passage was slowed. Participants either received no information about this blockage, or some kind of information indicating its presence. Information was delivered either verbally or through signage in the VR scene. The verbal information consisted of a computer-controlled avatar complaining aloud that evacuees were moving slowly due to a table in the way. The sign hung above the table, indicating its presence and advertising it as the location of a Boston trip sign-up sheet, with an arrow pointing down at the table itself (see Fig. 3). It did not follow any standardized formatting, and was intended to appear as if created and placed temporarily in the library by a student group, in keeping with the context. Smoke propagating from the edge of the library floor moved slowly and, due to the distance of its source, was not sufficiently dense to obstruct the participants' view of the sign in the High Hazard condition. The smoke partially occluded vision above head level, allowing participants to see clearly in front of them to walk forward (see Fig. 2 for representation of maximum smoke propagation). Smoke was constrained such that it never became so dense that participants could not see the sign (in conditions where it was present), the other evacuees, or their way forward. In both the verbal and signage conditions, delivery of the information was designed to be naturalistic and appropriate to the context of evacuation. A marker was placed in the physiological data at the time the participant first looked towards the obstruction to determine if the blockage resulted in further heightened anxiety (see sections 2.2 & 3.1). This marker is labelled "See Obstacle" in 3.1. The scene ended when the participant reached an exit, completing their evacuation – the simulation did not extend to stairwells or the lower floors of the library. In the course of reaching an exit all participants but one collided with one or more of the computer-controlled avatars evacuating alongside them. The first of these collisions, where present, was marked in the physiological data, and labelled as "First Collision" in section 3.1, in order to determine if there was an increase in anxiety due to the participants' path being obstructed by other evacuees.

Following the completion of the third VR scene participants were instructed to remove the VR headset and physiological sensors. The VR portion of the experiment routinely lasted approximately fifteen minutes, contingent on how long participants spent in the training scene and their speed during the evacuation scenes. Participants completed a survey containing questions about their VR experience, along with demographic information and other items included for exploratory purposes (See Appendix B for full survey). All experimental procedures were approved by the UConn Institutional Review Board.

3. Results

3.1. Physiological DVs

A series of paired t-tests were performed to test our predictions that changes in HR and GSR would occur at key events. T-tests compared the mean HR or GSR from a one second window immediately preceding the event to the max HR or GSR from a six second window beginning three seconds after the event in order to determine change from baseline. All means, standard deviations, and *t*-test results are presented in Table 1. As predicted, there were significant increases in GSR and HR at all markers, with the exception of HR at the "First Alarm" marker during the second scene.

Difference scores were then generated by subtracting the GSR Post Max and HR Post Max from the GSR Pre Mean and HR Pre Mean, respectively. The hypotheses that anxiety would increase more in the

Table 1
Changes in GSR and HR recorded at key events during VR simulation.

Event	Measure	Pre Mean	Pre SD	Post Max	Post SD	T	df	p
First Alarm								
	GSR	6.941	5.775	7.559	6.039	5.340	26	<.001**
	HR	80.297	14.323	81.927	14.911	1.530	26	.138
Evacuation Start								
	GSR	7.560	5.298	8.206	6.113	3.197	26	.004**
	HR	79.929	15.154	92.525	23.7	2.883	26	.008**
First Collision								
	GSR	7.549	5.561	7.669	5.624	2.430	25	.023*
	HR	82.968	17.837	91.782	24.927	2.970	25	.006**
See Obstacle								
	GSR	7.975	5.774	8.173	6.048	2.430	26	.022*
	HR	82.440	15.522	89.586	20.906	2.386	26	.025*

*significant at $p = 0.05$, ** significant at $p = 0.01$.
"Pre Mean" refers to the mean HR or GSR from a one second window immediately preceding the event of interest. "Post Max" refers to the maximum HR or GSR from a six second window beginning three seconds after the event of interest (See 2.2).

high hazard condition, but potentially be moderated by receiving information, were tested with analysis of variance (ANOVA). Due to sample size limitations, the original 2 (Hazard) x 3 (Information) design was collapsed to a 2×2 design for analysis of differences scores. Participants from both information conditions (signage and dialogue) were combined and compared to those participants who received no information. Differences scores from each event were submitted to 2 (Information) x 2 (Hazard) Between-Subjects factorial ANOVAs to determine differences in the change in GSR and HR between groups for all events after Information and Hazard were introduced (i.e., all except "First Alarm", which occurred during Scene 2). There was no significant main effect of either Information or Hazard, and no significant interaction effect of Information and Hazard, on HR difference scores at the First Alarm, Evacuation Start, First Collision, or See Obstacle events, $p > .05$. There was no significant main effect of either Information or Hazard, and no significant interaction effect of Information and Hazard, on GSR differences scores at the First Collision or See Obstacle events, $p > .05$.

There were also significant main effects of Information (F (1, 23) = 6.955, $p = .015$, partial $\eta^2 = 0.232$, $b = 0.714$) and Hazard (F (1, 23) = 4.313, $p = .049$, partial $\eta^2 = 0.158$, $b = 0.512$) on GSR difference scores at the Evacuation Start event. Participants who did not receive information (M = 1.180, SD = 1.700) had larger increases in GSR than those who did (M = 0.379, SD = 0.315). Participants in the low hazard condition (M = 0.454, SD = 0.364) had smaller increases in GSR than those in the high hazard condition (M = 0.925, SD = 1.159), indicating that those in the high hazard condition experienced a greater increase in anxiety, consistent with our expectations. However, Levene's test indicated a violation of the homogeneity of variance assumption of ANOVA, F (3,23) = 31.975, $p < .001$. Welch's test indicated that, with homogeneity of variance not assumed, there was no significant main effect of either Information (F (1, 8.276) = 1.964, $p = .197$) or Hazard (F (1, 10.725) = 0.934, $p = .355$) on GSR difference scores. Additionally, there was no significant interaction effect of Information and Hazard at the Evacuation Start event, $p > .05$.

3.2. Behavioral and self-report DVs

The 2 (Information) x 2 (Hazard) design was also used for analysis of behavioral and survey data. Participants from both information conditions (signage and dialogue) were combined and compared to those participants who received no information. Despite the difference in participants per cell caused by this alteration homogeneity of variance was maintained for all following analyses.

A 2 (Information) x 2 (Hazard) factorial ANOVA revealed a significant main effect of information on evacuation time, such that participants who received information about the obstacle (M = 90.413, SD = 38.511) evacuated significantly faster than participants who received no information (M = 127.860, SD = 42.776), F (1, 23) = 5.126, $p = .034$, partial $\eta^2 = 0.189$, $b = 0.581$. The homogeneity of variance assumption of ANOVA was not violated, F (3,22) = 1.288, $p = .303$. There was no significant effect of hazard on evacuation time, nor was there a significant interaction of hazard and information.

There was a significant positive correlation between evacuation time and participants' self-reported anxiety, such that those participants who reported higher anxiety also tended to take longer to reach an exit, $r = 0.464$, $p = .017$. Additionally, a 2 (Information) x 2 (Hazard) factorial ANOVA revealed a marginally significant effect of information on self-reported anxiety, where participants who received information (M = 4.278, SD = 1.504) reported less anxiety than participants who did not receive information (M = 5.389, SD = 1.269), F (1, 23) = 3.001, $p = .097$, partial $\eta^2 = 0.115$, $b = 0.382$. There was no significant effect of hazard on self-reported anxiety (F(1,23) = 0.194, $p = 0.664$), nor was there a significant interaction between information and hazard (F (1,23) = 0.140, $p = .712$). Homogeneity of variance was maintained for this analysis, F (3,23) = 0.459, $p = .714$.

A 2 (Information) x 2 (Hazard) factorial ANOVA also showed a significant effect of hazard on the total number of collisions made with computer-controlled avatars, where participants in the low hazard condition (M = 103.00, SD = 88.667) made fewer collisions than those in the high hazard condition (M = 190.360, 104.003), F (1, 23) = 5.540, $p = .028$, partial $\eta^2 = 0.194$, $b = 0.616$. Information did not significantly impact the number of collisions made, and there was no significant interaction of hazard and information. As above, homogeneity of variance was maintained, F (3,23) = 0.578, $p = .635$.

Chi-Square analysis of exit choice revealed that participants in the low hazard condition were significantly more likely than those in the high hazard condition to opt for peripheral exits over main exits, X^2 (1, 27) = 4.219, $p = .040$, despite similar levels of familiarity with the library setting. In the low hazard condition, 68.8% of participants used the main exits, while 31.2% opted for one of the peripheral exits. In the high hazard condition all participants used the main exits. Information did not have a significant effect on exit choice. Participants' exit choice significantly impacted their total number of collisions with other avatars, such that participants who chose main building exits (M = 153.963, SD = 101.869) collided with avatars more than participants who chose peripheral exits (M = 47.5, SD = 52.394), F (1,23) = 7.987, $p = .008$, partial $\eta^2 = 0.195$.

Participants consistently indicated on a Likert-type scale of one to seven, where one corresponded to "strongly disagree" and seven to "strongly agree", that the VR was realistic (M = 5.49, SD = 1.216), with no significant differences in reported realism due to Information or Hazard, $p > .05$. Participants generally indicated that they did not play video games (M = 2.86, SD = 1.80, where 1 = "Strongly Disagree" and 7 = "Strongly Agree"), and were therefore assumed to have little to no experience with VR prior to the experiment. Additionally, participants indicated near universal recognition that the building they were evacuating from was, in fact, the Homer Babbidge Library on a similar Likert-type scale (M = 6.54, SD = 1.325), with no significant differences in familiarity due to Information or Hazard, $p > .05$. Additional survey results, including those for exploratory items, are presented in Appendix C. Analyses here were performed on composite scores (e.g., for anxiety), and, as such, values in Appendix C differ.

4. Discussion

4.1. Findings and interpretation

As evinced by significant increases in participant HR and GSR, indicating increased anxiety, at key points in the VR scenes, the VR paradigm is sufficiently immersive to capture phenomena impacting egress route choice in emergency evacuations insofar as those phenomena stem from evacuee anxiety. [12] indicate that presence in a virtual environment is a precondition for, and not a product of, anxiety. With this in mind, significant changes observed in HR and GSR indicate that participants were engaged in the VR evacuation. In line with our expectations, providing participants with information indicating the presence of an obstacle partially occluding the most obvious route of egress decreased the time they took to exit the library floor. However, information did not significantly affect participants' exit choices. Though only marginally significant, trends in the data indicate that providing information can also decrease anxiety. Additionally, participants' self-reported anxiety was found to be positively correlated with evacuation time; those who indicated higher anxiety also tended to take longer to evacuate. Hazard level was found to affect competitive behavior and exit choice. Participants who saw fire and smoke during the final VR scene were more likely to use main exits and behave competitively (colliding with computer-controlled avatars) than those who did not see fire and smoke. Although hazard level was not found to have an effect on anxiety as we expected, the competitive behavior and sub-optimal exit choice exhibited by those in the high hazard condition are consistent with reports on real emergency evacuations where the danger is imminent [17]. In the event of a real fire emergency, any increases in anxiety are expected to be much larger than those observed in the VR evacuation. As such, there are possible effects of hazard on evacuee anxiety in real life which are not captured here.

On the basis of these results, VR appears to provide a useful avenue for exploring issues in evacuee behavior during fire emergencies, particularly those pertaining to anxiety. [23,24]. suggest that VR is useful in such situations due to its high internal validity, safety, and flexibility. However, they also indicate that VR requires confirmation or validation. The physiological data collected, along with survey items pertaining to realism and familiarity, indicate that the VR scenarios used in the current experiment are sufficiently immersive and lifelike to provide reliable information on evacuee behavior. Of course, *how strongly* individuals respond physiologically to the events in VR relative to a real evacuation cannot be assessed unless it were possible to validate the level of changes by experimentally inducing such an apparent emergency in the actual library.

Similar to [15]; participants here recognized and responded appropriately to the emergency situation, even when they were given no advance warning or instruction, as in the second VR scene. Combined with the effect of information on evacuation time, this seems to indicate that participants are not panicking, but rather making rational, if hurried, choices based on the current situation and the information made available to them. This lends credibility to the information-based theory of evacuee behavior presented in Ref. [1] and elsewhere. More puzzling is the relationship between information, evacuation time, and exit choice. The fact that participants who were provided with information reached an exit in less time than those who did not receive information, despite information not significantly affecting exit choice, may indicate that the information provided was not sufficient to draw attention to peripheral exits, or to make participants consider them as viable options. In all experimental conditions, the majority of computer-controlled evacuees opted for main exits, thereby exerting influence on participants to do the same [23,24]; this may have negated the effect of information on exit choice. Additionally, the information provided was not designed to directly influence exit choice, nor was it likely the correct type to do so. [30] indicate that, for maximum effectiveness, dissuasive emergency signage ought to clearly negate a provided exit message (e.g., a red X placed across the entire surface of an existing exit sign). The information provided in the current study indicated the presence of an obstacle, but did not explicitly state that a particular exit was unavailable, or instruct participants to seek an alternate exit. [5] found that signage offering directional information which contradicted the information provided by the movement of a crowd of evacuees decreased the proportion of participants following the crowd. This finding was not corroborated here, likely due to the fact that the information did not directly contradict the crowd movement. The extent of the reduction in evacuation time observed in the information condition of the current study was similar to that observed by Tang et al. [52]. Again, however, the nature of the information provided differed. Tang et al. [52] introduced signage indicating the presence of exits, whereas the signage in the current experiment informed participants about an obstacle. Information in the current study was intended to attenuate anxiety by reducing participants' uncertainty regarding the reason for crowding and slow movement. With reduced anxiety, and therefore reduced attentional narrowing, participants were expected to be more likely to notice and utilize peripheral exits. Information providing explicit instruction to evacuees regarding exit choice, similar to that employed by Ref. [5,30]; would likely result in significant differences in exit choice. The applicability of the theory of socially-mediated affordances [13] remains an open question, requiring more research into the specific effects of avatars' egress routes. However, as the perception of affordances is theorized to depend on information in the environment [16,38], and the theory of affordances has been successfully applied elsewhere in fire evacuation research, the outlook is good.

4.2. Limitations

Some limitations in using VR experiments to study evacuee behavior remain. Our pilot study featured one participant at a time evacuating amongst many computer-controlled avatars with predetermined paths. VR of this type cannot capture emergent behavior owing to the participants' choices and interactions. In real fire emergencies, the time required for any given evacuee to reach an exit is affected by such emergent factors (e.g., adaptation to congestion levels). However, as they are absent from the current VR simulation, participants' time to reach an exit may be taken as a result of their individual actions. A better understanding of emergent effects would require multiple participants evacuating concurrently in VR. This would also provide an opportunity to assess the effects of dynamic and ongoing communication between evacuees. As information is hypothesized to help direct participants towards peripheral exits and decrease egress time, understanding how information disseminates in a crowd of evacuees is imperative. The particular VR apparatus used in the experiment may also have affected our results. The movement speed of participants' avatars was naturally self-limited by the track-ball mouse participants used to control movement. However, this may have produced a ceiling effect on movement speed due to the physical constraints of the device. This may be problematic if such a ceiling exists, and if it is other than an evacuee's top speed in real life. Only summary data was available from the VR simulation, not trajectories or movement speed. The relationship between movement speed, flow, and evacuee density necessarily impacts variables of interest such as time required to evacuate [51], and bears further investigation here. Smoke is also understood to negatively affect the movement speed of evacuees [22,36,53]. Although hazard did not significantly affect evacuation time, it is unclear if or how it affected movement speed. It may be the case that, while exposure to hazard encouraged faster movement, the presence of smoke negated this effect, resulting in no significant difference in exit time. Additionally, current understanding of the effect of smoke on movement speed derives primarily from research on real and artificial smoke in non-VR environments [14,22], and applications in modeling evacuee behavior [37]. It is not currently known if and under what circumstances comparable effects can be expected in VR. This is understood to impact interpretation of the results of the current study, and warrants future investigation.

The third (experimental) scene of the VR simulation examined only evacuee behavior on the third floor of the library. This area was chosen so that participants would have near-universal awareness of the main exits, but likely little to no experience with ever using peripheral exits, putting them roughly on par with the familiarity parameters employed in FDS + Evac for generating computer-controlled avatar paths. Given that the layout of the building differs by floor, and that participants were highly familiar with the library, their pre-existing knowledge of the lower floors may have impacted their choice of exit on the third floor. The current study did not examine any possible effects of knowledge of the lower floors, which replication with naïve participants or a novel environment could elucidate.

An additional limitation of this pilot study is that it had a small sample size, and thus lower statistical power to detect main effects of information and hazard, and any interactions, on outcomes such as exit choice. Collapsing the verbal and signage information conditions into one for analysis did improve power, but hinges on their being sufficiently comparable. The nature of the information offered by each was the same, though they may differ in terms of salience or trustworthiness. Additionally, any mediating effect of anxiety can only be inferred. Physiological DVs indicate VR's ability to induce anxiety – sussing out the exact role anxiety plays will require greater power and further refinement of procedures. Finally, is not possible to check the observed changes in anxiety in this experiment against those which would occur in a non-VR fire evacuation. While increases in anxiety are to be expected in both situations, their extent and their effects cannot be compared without a real-world benchmark. However, obtaining such a benchmark poses significant challenges. Anxiety experienced in VR is assumed to be less than that experienced in real fire evacuations due to the absence of deleterious effects of not evacuating quickly. In future studies, VR might be augmented by the application of heat or presence of artificial irritant smoke, thereby increasing its verisimilitude and ability to induce anxiety in participants, within ethical limits. The anxiety discrepancy is understood to be problematic if the relatively higher anxiety experienced in a real evacuation results in behaviors not comparable to those observed in VR. As such, the effects of differing levels of anxiety warrant further investigation.

4.3. Conclusions and future directions

Given that VR is shown capable in this pilot study of inducing anxiety, as indicated by physiological measures, at appropriate moments analogous to those which might occur in a real emergency evacuation, and that information provided to participants is effective in reducing the time required to evacuate, the next steps would be to adjust the information and the method of its deployment to maximize its utility to evacuees. It may be the case that information about the layout of the environment, as provided in the current study, is not sufficient to draw evacuees to peripheral exits, especially in the presence of strong social influence (i.e. the route and exit choices of others). Explicit direction may be required to increase utilization of peripheral exits and further decrease the time required to evacuate. However, such direction in real-life evacuations would require dynamic tracking of the locations of building occupants. The obstacles and available egress routes in a real evacuation are dynamic. As crowds move and fire and smoke propagate, exits will become more or less safe and efficient. If it is the case that information of the type provided here can reduce the anxiety of evacuees, it may help improve the effectiveness of more explicit direction by reducing competitive behavior and associated effects. Further iteration is required to determine the ways in which psychological factors, environmental affordances, and social influence interact to affect route and exit choice. With some modification, VR provides a suitable testbed for methods of providing specific and dynamically updated guidance to evacuees. The library setting used in the current pilot experiment, with its convoluted layout and multiple exits, is ideal for future testing of evacuation behavior under a variety of circumstances. On the whole, VR's versatility makes it ideal for assessing many factors which may impinge on evacuation efficiency, so long as the particular VR simulation aims for and is assessed on its ability to achieve high levels of mundane, experimental, and psychological realism [46]. While VR may never, and for ethical reasons likely should not, fully replicate the experience of being involved in a fire emergency, it represents a major step forward in terms of the validity and flexibility of lab based research.

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Appendix A

FDS + Evac burner parameters

Surface ID: BURNER
Surface Type: Burner
Heat Release Rate Per Unit Area: 500.0 kW/m^2
Mass Loss Rate: 0.0 kg/(m^{2}s)
Extinguishing Coefficient: 0.0 m^{2}s/kg
Boundary Conditions Model: Fixed Temperature
Surface Temperature: TMPA = 20^c
Net Heat Flux: 0.0 kW/m^2
Convective Heat Flux: 0.0 kW/m^2
Ramp-Up Time: 1.0s
Soot Yield: 0.01
Emissivity: 0.09

Ventilation

Surface ID: OUTFLOW
Surface Type: Exhaust
Volume Flow: 0.0 m^3/s
Velocity: 1.0e–06 m/s
Total Mass Flux: 0.0 kg/(m^{2}s)
Tangential Velocity: 0.0 m/s
Ramp-Up Time: 0.1s
Wind Profile: Top Hat

Active fire protection elements

None modeled

Appendix B

Evac study questionnaire. #1–14 are likert-type, scale of 1–7

1. I felt anxious during the evacuation
2. I recognized the building I was in.
3. During the evacuation, I felt concerned about whether I would be able to get out before the fire got too close.
4. The behavior of the other people during the evacuation seemed about what I would normally expect.
5. I was relaxed during the evacuation.
6. I did not trust that the other people in the building would be making the best decisions about getting out of the building.
7. During the evacuation, I was surprised by the exits the other people were taking.
8. I play video games.
9. I was stressed during the evacuation.
10. I assumed that other people in the building probably knew where they were going.
11. I am good with computers.
12. I felt calm during the evacuation.
13. I was confident I was going to get out of the building in time.
14. The experiment seemed unrealistic.
15. Demographic/Background Information, Age, Gender, Ethnicity/Race

Appendix C

Means and Standard Deviations for all survey items, by condition. Items Q1–14 correspond to those in Appendix B.

	Low Hazard				High Hazard			
	No Info		Info		No Info		Info	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Q 1	6.00	1.55	4.22	2.11	4.67	2.52	4.11	1.45
Q 2	6.83	0.41	6.33	2.00	4.67	2.52	6.67	0.71
Q 3	5.33	1.86	4.11	2.62	6.00	1.00	5.11	1.54
Q 4	4.17	0.75	4.44	2.13	1.67	0.58	3.11	1.69
Q 5	3.33	1.97	4.22	2.11	2.00	1.00	3.22	0.97
Q 6	4.5	2.17	4.56	2.07	4.00	1.00	4.33	1.58
Q 7	3.67	1.21	4.33	2.06	3.33	0.58	3.56	1.59
Q 8	3.5	1.76	3.78	2.39	1.00	0.00	2.11	1.27
Q 9	5.83	1.47	3.89	1.90	5.00	2.00	4.00	1.87
Q 10	5.67	1.51	5.11	1.833	5.00	2.00	5.56	1.01
Q 11	5.33	1.211	4.89	0.78	3.33	1.16	3.89	1.17
Q 12	3.00	1.27	3.67	1.87	2.00	1.00	2.89	1.17
Q 13	3.67	1.97	3.89	1.74	2.33	1.16	4.22	1.72
Q 14	2.17	1.17	2.22	1.39	3.00	1.73	2.89	1.36

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