A Sequence Analysis of Behaviors in Immersive Virtual Reality for Indoor Earthquake and Post-earthquake Evacuation

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Abstract

Behavioral sequence analysis (BSA) gives insights to understand and model individual behaviors. The present study uses BSA for a virtual earthquake. The virtual earthquake drill was facilitated by a head-mounted display (HMD)-based immersive virtual reality (IVR) system. Eighty-three participants experienced a full earthquake and post-earthquake evacuation in a virtual hospital building. Concurrent verbal protocol analysis (VPA) and retrospective video analysis of the footage of participants' in-IVR behaviors have been conducted to identify the behavioral sequence of participants. As a result, behavioral transition diagrams are generated, showing the progression of behaviors exhibited in the virtual earthquake drill. A variety of behavioral paths for each individual participant is presented using a visual analytics approach. The behavioral transition diagrams and behavioral paths expose the full picture of human behaviors in an earthquake emergency, which are vital to developing behavior-oriented strategies for earthquake emergencies.

Keywords: Behavioral Sequence Analysis; Action Sequence Analysis; Verbal Protocol Analysis; Think-aloud Protocol Analysis; Earthquake Behavioral Responses; Behavioral Path

1. Introduction

Understanding how building occupants respond to earthquake emergencies is key to developing effective risk reduction strategies. Based on human behaviors in earthquakes, building designs and facility plans can be improved to provide better protection, and education and training can be more focused on informing appropriate behavioral responses during earthquakes [1]. Efforts have been made to identify the factors influencing human behaviors during earthquake emergencies, such as the position of a building occupant, the characteristics of a building occupant, the building context to a building occupant, and the intensity and duration of an earthquake [2-5]. These studies have established the foundations of behavioral analysis for earthquake emergencies.

There are several ways to collect data on human behaviors that occur in an actual earthquake, such as interviews, surveys, and video analysis. Interviews and surveys are conducted retrospectively, where post-event reflection is necessary. This type of data may suffer from recall bias, resulting in misleading information [6,7]. In addition, traumatic experiences can lead to post-traumatic symptoms that can cause memory loss and alteration [8,9]. In turn, video analysis relies on the availability of the video footage that captures earthquakes, such as closed-circuit television (CCTV) recordings and videos made by building occupants using mobile devices or cameras [10-12]. As a result, this data source is limited as it is not practical to expect much video footage to be retrieved after an earthquake. Therefore, it is challenging to get a full picture of human behaviors over an entire earthquake event based on video analysis.

In addition to the behavioral data collected from actual earthquakes, some studies have employed experimental settings, such as earthquake simulation and drills [13-15], which allow for real-time observation and data collection over an entire earthquake without missing any relevant information. With interviews or surveys conducted immediately after experiments, retrospective data suffer less from recall bias, memory loss, and memory alteration. However, these experimental settings share one major limitation: less ecological validity than real-world cases. Ecological validity refers to the extent to which an experimental method or setting is representative of a real-world scenario [16]. Regarding earthquake simulation and drills, they are models of actual earthquakes that contain assumptions and simplifications [17-19]; the hazards, evacuation population, behavioral responses, and social interaction in earthquake simulation and drills may be simplified, leading to a relatively low level of ecological validity in some cases [15,20]. As a result, the behavioral data collected from these experimental methods might differ from those obtained from actual earthquakes [21].

In terms of experimental settings, an alternative solution is to use immersive virtual reality (IVR) technology to run earthquake drills. IVR is a type of computer-generated simulation that allows participants to be immersed in virtual environments and events [22,23]. IVR makes it possible to expose participants to realistic hazardous events, which would be risky and unethical to do in the real world [24]. Virtual earthquake drills in IVR can be considered a type of earthquake simulation, sharing the same advantage (i.e., real-time observation throughout a complete event) and limitation (i.e., ecological validity) discussed in the previous paragraph. However, strong evidence supports the claim that IVR can induce realistic behavioral and emotional responses, enhancing ecological validity [25-29]. This claim is supported by previous studies showing that immersive environments can evoke similar responses to those observed in physical environments, including a strong sense of presence in an earthquake simulation [30], emotional reactions [31], and spatial perception [32]. Higuera-Trujillo et al. [33] examined the differences in psychological and physiological responses between an IVR simulation and a corresponding real environment and show that IVR offers the closest-to-reality representation with respect to users' physiological responses and that physiological and psychological responses correlate with the sense of presence. Therefore, IVR can provide insights into human behaviors in extreme situations [22,23,34]. Another advantage of IVR is that it provides a high experimental control level, making it possible and easy to adjust experimental settings and replicate experimental results [35]. Benefiting from this, IVR could outperform real-world field settings and conventional laboratory experiments in terms of internal and external validity, which makes it an ideal tool for behavioral studies [35,36]. However, IVR still faces a few challenges, such as motion sickness, vision requirements, control differences, and limited multi-user interaction [35]. Acknowledging its discrepancies with the real world, IVR can be a complementary tool to field experiments instead of a replacement [37].

There are several ways to collect behavioral data from IVR. One of them is to record the IVR experience of a participant and output it as video footage, showing the explicit behaviors of participants within IVR. The video footage can be coded to obtain observed human behaviors, referred to as the revealed behavioral data, for further behavioral analysis [38,39]. This is similar to video analysis based on the video footages of an actual earthquake and can give the full picture of the behaviors from the beginning to the end of an earthquake event. In addition to revealed behavioral data, another type of collectable data is stated preference. Instead of using interviews or surveys to collect this type of data in a retrospective way, it is possible to concurrently collect stated behavioral data using verbal protocol analysis (VPA) while a participant is experiencing a virtual earthquake within IVR. The concept of VPA is to verbalize thoughts concurrently with the execution of a task; therefore, to give insights into what, how, and why actions are taken [42-44]. While it is unlikely to plan VPA for an actual earthquake, VPA can easily be applied with a virtual earthquake in IVR [45].

While previous studies have investigated the variety of behavioral responses that occurred in earthquakes and the influencing factors on behavioral responses, little attention has been paid to behavioral transitions and sequences [2,11]. Behavioral sequence analysis (BSA) exposes the dynamic relationships within a series of actions or social interactions taking place over a period of time [41,46,47]. It can be a useful method to inform the behavioral patterns and relationships in the case of an earthquake emergency [48]. As such, the aim of the present study is to investigate the behavioral responses and sequences occurring in earthquakes and post-earthquake evacuation. Research questions include 1) What are the actions taken by building occupants in an earthquake and post-earthquake evacuation process? and 2) What are the transitional pathways of these actions? The present study uses VPA in an IVR setting and BSA to achieve sequence analysis. First, a review of IVR, VPA, and BSA is outlined in Section 2. Second, a case study using IVR and VPA is demonstrated in Section 3, including an IVR system, participants, procedures, and data collection and analysis. Finally, BSA results are presented and discussed in Sections 4 and 5, leading to the limitations of the present study and future research areas.

2. Research methods

2.1 Immersive virtual reality

IVR has been widely applied to study human behaviors in emergency situations, such as building evacuation [49], fire [50], earthquakes [45], and flash floods [51]. Lin et al. [49] studied herd behavior in the case of building evacuation. Results indicate that individuals tend to follow the crowd during evacuation, which are consistent with the findings from the real world. Xia et al. [52] investigated the impacts of emergency broadcasts on evacuation behaviors. Results show that emergency broadcasts have a strong influence on evacuation behaviors. This finding is in line with prior studies that suggested the importance of emergency broadcasts to guide evacuation behaviors. Ming et al. [37] examined the impacts of route turning angles on behavioral compliance. Results suggest that route turning angles can alter behavioral compliance with emergency signage. This finding implies that the perspective of evacuees is also an important factor in evacuation design. Feng et al. [53] observed pedestrian exit choice using IVR. Results confirm that the exit choice behavior in IVR is similar to that found in field experiments. However, previous studies did not utilize IVR to investigate emergency behavioural transitions and sequences. We have reconstructed an IVR earthquake scenario in the present study to allow for behavioral sequence analysis

(BSA).

2.2 Verbal protocol analysis

Verbal protocol analysis (VPA) is an approach to uncover cognitive activities and behaviors [54]. Participants need to verbally express their thoughts while carrying out activities [55]. Therefore, VPA is also known as a think-aloud protocol. VPA makes it possible to explicitly scrutinize underlying behaviors and decision-making processes [56]. VPA has been applied to investigate different types of human factor constructs, such as decision-making [57,58], problem-solving [59], awareness [60], distraction [61], and cognitive strategies [62]. In addition, studies have used VPA to examine behaviors and reasoning in emergency situations [45,63].

In general, verbal protocols can be executed either concurrently or retrospectively [54]. Concurrent verbal protocols mean that thoughts are verbalized while conducting an activity; meanwhile, retrospective verbal protocols consist of verbalizing thoughts immediately after the completion of an activity [54]. Retrospective protocols may be more problematic than concurrent protocols in terms of veridicality [44,64]. Veridicality refers to the completeness, exactness, and truthfulness of information [65]. Due to memory decomposition, retrospective protocols may produce less richness of information than concurrent protocols (e.g., forget to report a piece of thought) [63,66,67]. In addition, retrospective protocols may give misleading information due to recall bias (e.g., report fabricated thoughts unconsciously) [65]. However, concurrent verbal protocols may be distractive, leading to the alteration of response time and decision-making outcomes [67-71]. According to Ericsson and Simon [44,54], if participants report their thoughts rather than make efforts to explain them, concurrent protocols have no fundamental effects on the output of decision-making.

Although VPA has limitations, it is still an effective tool to expose implicit behaviors and cognitive activities [57,65,72,73]. In the present study, we have decided to apply concurrent verbal protocols. The objective is to obtain comprehensive information about the real-time behavioral responses in earthquake emergencies, which is difficult to get in real-world cases. There is a gap in the literature regarding VPA for earthquake emergencies as it is impossible to be planned. Thanks to IVR, the present study uses VPA for earthquakes in an IVR setting.

2.3 Behavioral sequence analysis

Behavioral sequence analysis (BSA) is an approach to investigate the transitions and relationships between individual behaviors [41,46,47]. BSA can generate a map showing the progression of behaviors within a particular event or a timespan [41,74]. BSA has been applied in various domains to understand behaviors and social interactions, such as criminal cases [75], nonverbal communication [41], martial interaction [76], and fire evacuation [48]. BSA echoes the concept of Markov models, which focuses on the transitions between behavior pairs [77]. A behavior pair includes an antecedent and a sequitur, representing the initial behavior and its subsequent behavior. It is possible that one antecedent leads to multiple sequiturs, and one sequitur results from multiple antecedents. The essential output of BSA is a demonstration of which sequitur is more likely to occur than by chance following an antecedent [77].

In general, there are three major steps involved in BSA: unitization, classification, and analysis [78]. Firstly, unitization means breaking down the whole set of behavioral responses or social interactions into individual pieces of discrete behaviors. Secondly, classification consists of coding and categorizing discrete behaviors. Functionally similar behaviors are given the same code and placed into the same category. At this stage, the whole set of behavioral responses can be displayed as a string of codes (e.g., 1, 2, 3, 4), where each code represents a discrete behavior. Lastly, analysis takes place. This step involves analytic approaches to the transitions between behavior pairs (e.g., 1-2, 2-3, 2-4, 3-4). For instance, statistical measures can be taken to determine which subsequent behavior is more common following an initial behavior (e.g., 3 is more common than 4 following 2).

There are various ways to report the output of BSA. For instance, Marono et al. [41] produced state transition diagrams of behaviors to exhibit the behavioral sequence of individuals when answering questions. Similarly, Keatley and Clarke [75] proposed a waypoint sequencing diagram to illustrate the key events of criminals in their case histories, providing a simplified sequence of the main behaviors of interest. Also, Nguyen et al. [82] demonstrated a visual analytics approach to indicate the behavioral sequence of internet users. This visual analytics approach involves color-coded squares to represent actions and their temporal order, establishing the behavioral paths of different types of internet users.

BSA has been implemented in different domains. However, the literature lacks the sequence analysis of behavioral responses in earthquake emergencies. Therefore, the present study applies BSA to reveal the behavioral transitions and paths in earthquake emergencies.

3. Experimental design

We conducted an experiment trying to answer the research questions raised in Section 1. This experiment involved a virtual earthquake drill using IVR. Human participants were recruited to experience the virtual earthquake drill. Their actions and verbal protocols illustrated in IVR were observed and recorded. Based on this behavioral data, BSA was conducted to elicit behavioral transition diagrams and behavioral paths, reporting the behavioral sequence of participants in an indoor earthquake and post-earthquake evacuation. This section provides the details of the experimental design, covering the IVR system, experiment setup, participants, procedure, and data collection and analysis.

3.1 IVR system

The IVR environment was modelled using an actual building, which forms part of the Auckland City Hospital. We followed a Building Information Modelling (BIM)-based workflow to develop the virtual environment [30]. The BIM-based workflow allows a realistic virtual environment with the capability for dynamic changes, which is helpful to simulate credible earthquakes in IVR [79]. We referenced the building's floor plans and site photos to build a building model using Autodesk Revit 2017. This building model was converted to a Filmbox (FBX) model, which was then imported into Unity 5.5.1 for further IVR development. Figure 1 shows the layout of the virtual environment. In order to simulate an earthquake and post-earthquake damage, we applied non-structural damage to the virtual environment based on a qualitative approach (i.e., a descriptive approach without physical and mathematical modelling). We referred to the New Zealand Modified Mercalli Intensity (MMI) scale 6 and 7, which include earthquake-related impacts in buildings such as falling ceiling panels, breaking glass, toppling partition walls, shifting furniture, and rattling small objects (Figure 2.g) [80]. Sound effects such as creaking, rattling, and breaking were applied along with visual effects. Non-player characters (NPCs) were used to represent building occupants in the virtual environment. NPCs represented building occupants other than the participants exposed to the IVR environment. NPCs were programmed to carry out activities following predefined scripts, such as having conversations with participants, responding to earthquakes, and evacuating the virtual building. Participants could move freely in the virtual environment within a defined area as an open-world environment. However, to encourage participants to follow and complete the storyline of the IVR scenario, we allowed movement and activities to be taken only within the areas that were part of the storyline (non-hatched areas in Figure 1). In addition, we provided guidance in IVR to help participants follow the storyline, such as “turn left and go to the meeting room”, mostly before the commencement of the earthquake. Navigation was accomplished in a way by pressing a button on a controller to walk towards facing directions. Participants could turn their bodies and heads around to change directions in the virtual environment. Participants could also click the same button on the controller to virtually crouch when they looked down to the ground. The full prototyping process of the IVR scenario can be found in Lovreglio et al. [30].

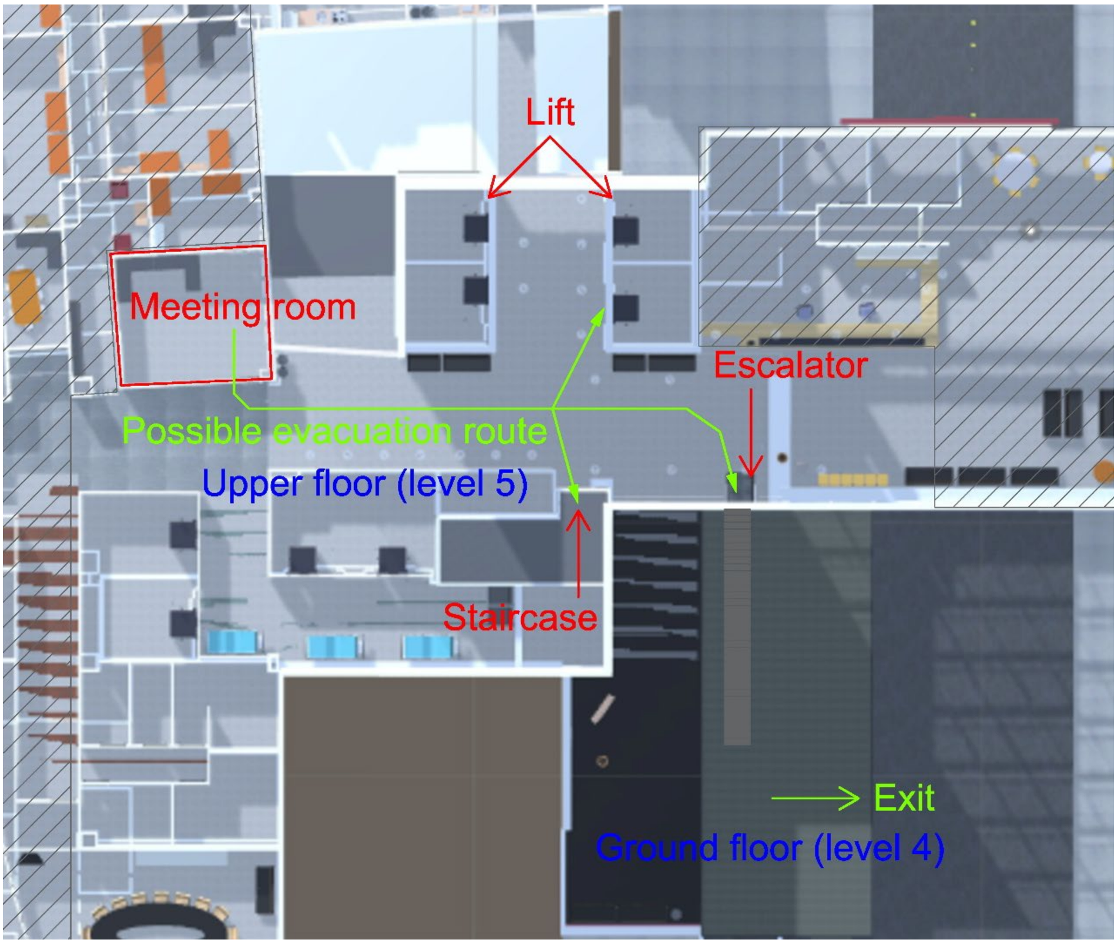

Figure 1 – The layout of the virtual environment (the hatched area is constrained for movement and activities) [45]

The IVR scenario was designed to allow for observation of the behaviors of participants in response to earthquake emergencies. Therefore, the IVR scenario did not provide prompts, instructions, hints, or feedback to participants in terms of the procedures to deal with earthquakes. Participants could execute their behaviors as they willed. The storyline of the IVR scenario from a first-person perspective in a single user environment follows the steps below (see Figure 2 for illustrations) [45]:

1. Once the IVR scenario is loaded, participants are standing outside the hospital building on the ground floor, front door (i.e., level 4).
2. Participants enter the building and take an escalator to the upper floor (i.e., level 5).
3. Participants enter a meeting room on the upper floor and meet a Doctor NPC and a Visitor NPC.

4. The Doctor NPC starts a conversation with participants. Participants put their keys and mobile phone on a table in the meeting room.
5. The building starts to experience an earthquake. The Doctor NPC says, "What happened? It is an earthquake". Then the Doctor NPC and Visitor NPC execute drop, cover and hold.
6. Objects start rattling and falling, furniture starts shifting, a glass window starts creaking and breaking, a photocopier in the corner of the meeting room starts emitting electric sparks.
7. Participants can make their own decisions about how to respond to the earthquake. They can even decide to escape; however, they cannot leave the meeting room as the door is temporarily locked. This is to let participants complete the rest of the storyline so that the observation on the behavioral responses in a complete earthquake event can be achieved. If participants decide to escape at this point, this behavioral response is recorded.
8. The earthquake dissipates after 60 seconds. The Doctor NPC stands up and starts to look around. Then the Doctor NPC decides to check the situation outside the meeting room. The Doctor NPC tells participants to wait in place. The Visitor NPC gets up and starts trembling in fright.
9. There are debris and fallen objects around the meeting room. There are a radio, a coffee machine, and a water cooler in the room and a laptop, a set of participant's keys, and a participant's mobile phone on the table. There is a faulty photocopier that continues to emit electric sparks. There is a first aid kit on the wall next to the meeting room door.
10. Participants can make their own decisions about how to respond to the post-earthquake situation. They can do whatever they want in the meeting room or start their evacuation before the return of the Doctor NPC.
11. The Doctor NPC returns to the meeting room after 60 seconds and says to leave the building with him. The Doctor NPC and Visitor NPC start to leave the meeting room.
12. A group of NPCs are evacuating while participants are making their way out through the corridor on the upper floor.
13. The Doctor NPC and Visitor NPC choose a staircase to descend to the ground floor. Participants can decide whether to use a lift, the escalator they used before, or a staircase to descend.
14. Participants reach the main entrance of the building on the ground floor. The Doctor NPC stands close to the main entrance while three groups of NPCs gather outside the building. Participants can decide whether to join others at an assembly point or stay with the Doctor NPC.

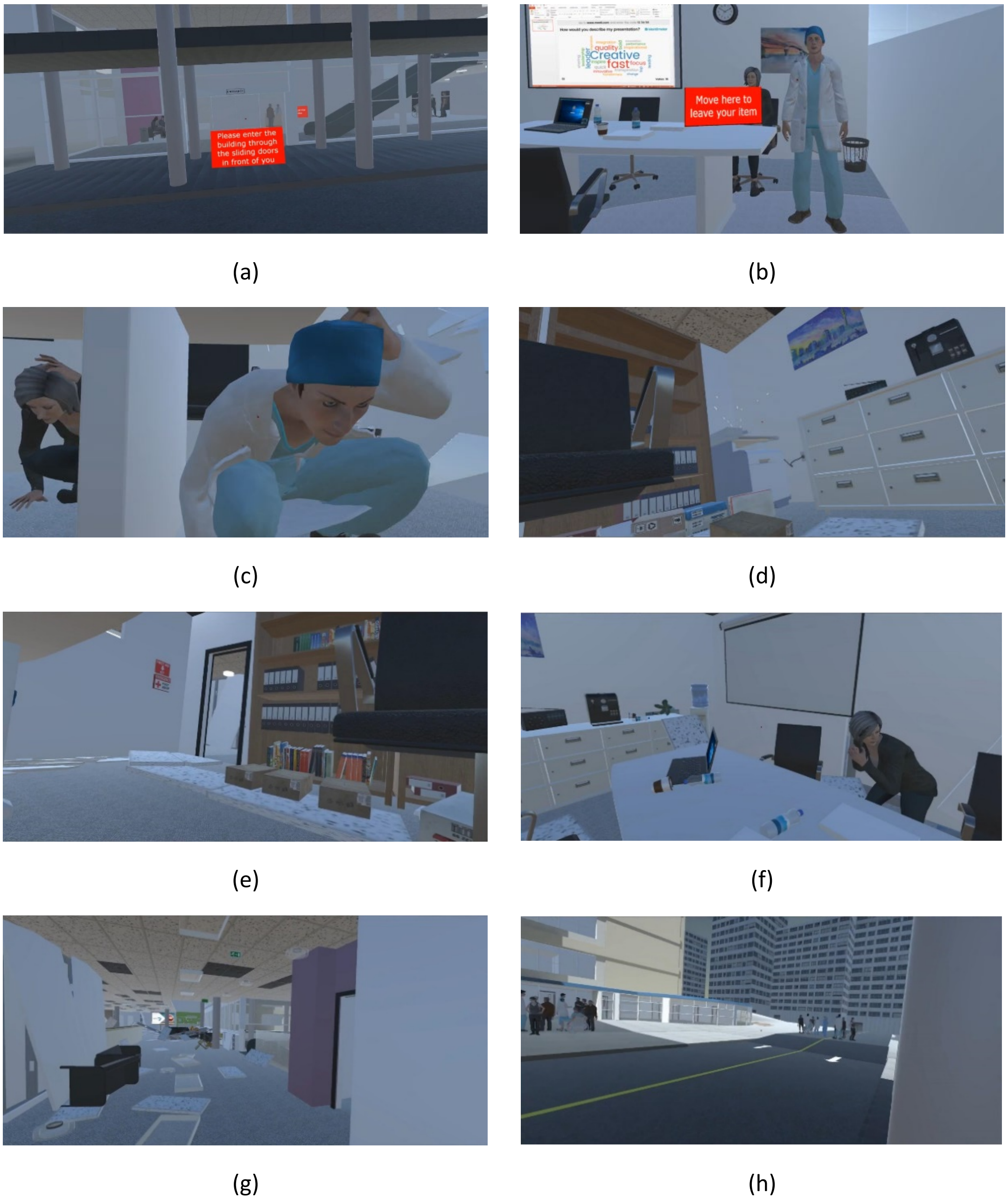

Figure 2 – The storyline of the IVR scenario: (a) Beginning of the IVR scenario, outside the hospital building; (b) Before the earthquake, inside the meeting room; (c) During the earthquake, inside the meeting room, both NPCs execute drop, cover, and hold; (d) During the earthquake, inside the meeting room, a photocopier starts emitting electric sparks; (e) During the earthquake, inside the meeting room, objects start falling; (f) After the earthquake, inside the meeting room; (g) After the earthquake, outside the meeting room; (h) After the earthquake, outside the hospital building [45]

3.2 Experimental Setup

A desktop computer workstation running Windows 10 was used to host the IVR scenario in Unity 5.5.1. The computer has a 2.4 GHz Intel Xeon E5-2640 processor, 64

GB of RAM, and two Nvidia Quadro M5000 graphics cards. The IVR scenario was displayed using an Oculus Rift, which is a head-mounted display IVR headset with one Oculus Remote and two tracking sensors. The visual outputs of the IVR headset were displayed simultaneously on the monitor of the desktop computer workstation. A built-in microphone on the IVR headset received the verbal protocols of participants. In addition, physical vibration was applied to participants through a shaking platform during the virtual earthquake in the IVR scenario. This shaking platform has an audio power amplifier that receives and amplifies the audio signal from the desktop computer workstation (i.e., the sound effects of the earthquake in the IVR scenario) and sends the signal to a motor to create vibrations. Therefore, participants could simultaneously experience a virtual earthquake and feel a physical shaking dimension. Figure 3 shows the setup of the apparatus.

Figure 3 – The setup of the apparatus [30]

3.3 Participants

Several approaches were adopted to recruit participants, including posts on staff newsletters through the intranet of Auckland District Health Board and posters and leaflets distributed around the Auckland City Hospital and the University of Auckland. Participation Information Sheets informed potential participants that they would go through IVR simulation where normal vision is essential (it is possible to use personal glasses). There were no other screening criteria to select participants. As a result, a total of 87 participants were involved in the present experiment, including 42 females and 45 males. However, four participants could not complete the entire IVR scenario due to motion sickness. The demographics of the remaining 83 participants are reported in Table 1. Over three-quarters of participants were aged between 20 and 49. Participants also stated their prior experience with fire and earthquake drills, as shown in Table 2. Most participants have little training experience with earthquake emergencies. In addition, participants evaluated their awareness of and preparedness for earthquake emergencies in terms of appropriate behavioral responses. Results are displayed as boxplots in a 7-point Likert scale, where -3 stands for unprepared and +3 means prepared (Figure 4). In general, participants did not feel well-prepared for earthquakes (M = 0.57, SD = 1.66). Finally, participants reported their previous experience with IVR before the experiment. Thirty-six participants (43.4%) gave a positive confirmation, 46 participants (55.4%) claimed no experience, and one was unsure about it.

Table 1 - The demographics of the participants

	n	%
	Total n = 83	
Sex		
Female	38	45.8%
Male	45	54.2%
Age range		
< 20	2	2.4%
20-29	25	30.1%
30-39	25	30.1%
40-49	13	15.7%
50-59	11	13.3%
60-69	6	7.2%
70-79	1	1.2%

Table 2 - Experience with fire and earthquake drills

Frequency	Fire drills		Earthquake drills	
Never	21	25.30%	69	83.13%
Once a year	27	32.53%	7	8.43%
Twice a year	19	22.89%	2	2.41%
More than twice a year	10	12.05%	0	0.00%
Unsure	6	7.23%	5	6.02%

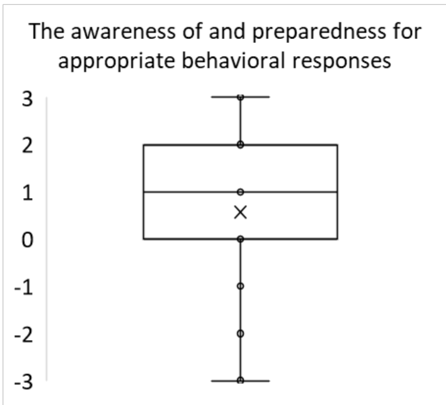

Figure 4 – The awareness of and preparedness for appropriate behavioral responses in earthquake emergencies

3.4 Procedure

The University of Auckland Human Participants Ethics Committee issued the ethical approval to conduct the experiment. The Auckland District Health Board Research Review Committee granted institutional approval to proceed with the experiment. The experiment took place in a meeting room of Auckland City Hospital from July to August 2017. Participants learned about the purpose of the experiment through participation information sheets. Participants understood that the experiment involved IVR content which required normal vision; however, it was possible to wear personal glasses. The experiment was part of a larger research program in which two experiments were conducted in parallel simultaneously: one was an IVR-based earthquake training experiment, and the other was the one in this present study. Participants did not know which experiment they were going to be involved in. They were quasi-randomized to participate in one of the experiments. While participants could be aware of the exercise they were about to undertake, they had no clues to the levels of realism and immersion that they would be exposed to. As reported in Section 3.3, 55.4% of participants (46) never experienced IVR prior to the experiment. Also, the experiment setup included a shaking table to enhance realism and immersion. Participants acknowledged a high level of realism for the IVR scenario [30].

Upon arrival, participants signed consent forms that acknowledged their engagement with the experiment and the collection of data for research purposes. Participants were aware of their right to exclude themselves without giving any reasons at any time during the experiment. After completing the consent forms, participants completed questionnaires with information about their demographics and backgrounds, as shown in Section 3.3. Before putting on the IVR equipment, participants received inductions on health and safety and the use of IVR headsets and remote controllers.

Participants also completed an induction on how to perform VPA. After that, they sat in the swivel chair mounted on the shaking platform. Next, they put on the IVR headset and adjusted it to obtain a clear view inside it. Then, participants started a tutorial session in which they familiarized themselves with the navigation and interaction in IVR using an IVR headset and a remote controller. Meanwhile, participants performed trials using VPA with explanations and demonstrations. They were instructed to verbalize what they were doing and why. In both IVR and VPA tutorial sessions, participants were not disclosed with any details of the actual IVR scenario and experiment. Participants only practiced the general use of IVR and VPA. Once participants felt comfortable with IVR and VPA, they began the actual IVR scenario.

Participants went through the IVR scenario following the storyline presented in Section 3.1. They started verbal protocols as soon as they entered the meeting room and were welcomed by the Doctor NPC. Participants were expected to carry on verbal protocols till the end of the IVR scenario. If participants stopped talking for around ten seconds, researchers would gently remind them to keep speaking out their thoughts. Researchers did not interrupt or ask any questions. When participants completed the IVR scenario, they reached the end of the experiment.

3.5 Data collection and analysis

The behaviors of participants in the IVR scenario were recorded and saved as video footage. The recorded verbal protocols of participants were synchronized with the video footages into one video file (as in an MP4 format). These MP4 files were the primary datasets for data analysis, which were transcribed and coded by two researchers independently. The coding process was conducted across three sections of the IVR scenario, representing three key stages of earthquake emergencies:

A. Participants were in the meeting room when an earthquake started to impact the building.
B. Participants were in the meeting room when the earthquake stopped.
C. Participants started to leave the meeting room for evacuation after the earthquake.

The coding scheme included the participants’ behaviors performed within IVR and verbalized via verbal protocols. Behavior categories were created and updated by the researchers iteratively when apparent behaviors were identified. In addition, the occurrence of the behaviors was recorded and sequenced for each participant, including both actual behaviors within IVR and verbalized behaviors via verbal protocols. Table 3 gives an example of recognizing and sequencing behaviors. The results were cross-checked among the researchers with mutual agreement. With the identification of behaviors and their sequences, behavioral paths emerged for participants, including the behaviors taken in an order from the beginning to the end of an event.

Table 3 – Recognize and sequence behaviors for stage one of the earthquake emergency

Participants	Behaviors within IVR	Verbal protocols	Behavior recognition and sequence
P1	Walk to the table and get under it.	(While under the table) "I want to move the chairs away from me".	1. Take cover 2. Move loose objects away
P2	Look around, then get cover under the table.	"I'm now under the table".	1. Look around 2. Take cover
P3	No movement to take cover	"I want to get under that table".	1. Take cover

4. Results

4.1 Behavioral transition diagrams

Firstly, the frequencies of behaviors taken or verbalized by participants have been calculated (Table 4). Secondly, the transition frequencies between antecedents and sequiturs have been calculated and plotted into transition matrices, which is the main step of sequence analysis [41]. The transition matrices are large; therefore, they are available as Supplementary Material 1. Lastly, based on the transition matrices, behavioral transition diagrams have been developed for each stage, respectively (Figure 5, Figure 6, and Figure 7). Circles represent a particular behavior identified in Table 4, while arrows with solid lines demonstrate the transition of behaviors from antecedents to sequiturs. The positions of circles do not indicate temporal orders. The numbers on arrows are proportions followed by the frequencies of transitions in brackets [81]. A proportion stands for the proportion of participants who performed an antecedent and a sequitur subsequently. For instance, in Figure 5, five participants moved to the door of the room (a2). Subsequently, one of them took cover (a1). Therefore, the proportion of the transition from a2 to a1 is 20% (0.20). Returning arrows with dash lines mean participants did not take any further actions after a behavior (i.e., the end of behavioral engagement in a scenario). Following the previous example, four out of five participants (80%) did not take any action after moving to the door of the room (a4). Arrows with bold lines represent the most occurred transition among the transitions from an antecedent to its sequiturs (i.e., a transition with the highest proportion). For instance, following the previous example, the transition from a2 to a1 is the only and most occurred transition after moving to the door of the room (a2). Therefore, the arrow and solid line for this transition are bold. In order to have a meaningful presentation of behavioral transition diagrams, Klonek et al. [40] propose to omit a transition if its frequency is below five for large datasets, and Marono et al. [41] suggest a cut-off of three for small datasets. After assessing the complexity of our diagrams, we decided not to omit any transitions for Figure 5 and Figure 7. Regarding Figure 6, a cut-off of frequency of one was applied to improve the readability of the diagram. As a result, a few transitions, including the ones to and from 'Use the computer' (b7), are not displayed. The full list of transitions can be found in Supplementary Material 1.

Table 4 – Frequencies of behaviors

Behaviors with codes	Frequencies
Stage A: Earthquake starts	
a1: Take cover	79
Under a table	77
At a corner	1
Under a doorway	1
a2: Move to the door of the room	5
a3: Move to a corner	1
a4: Look around	2
a5: Check the mobile phone	1
a6: Move other objects away	12
a7: Care about others	20
a8: Check for hazards and damage	22
a9: Look for the first aid kit	1
Stage B: Earthquake stops	
b1: Check for hazards and damage	56
b2: Care about others	43
b3: Collect the mobile phone	21
b4: Wait for further instructions	13
b5: Use the radio	3
b6: Collect the first aid kit	6
b7: Use the computer	3
b8: Unplug the photocopier	13
b9: Make a phone call	10
b10: Collect keys	7
Stage C: Evacuation starts	
c1: Evacuate with the Doctor NPC	57
c2: Evacuate alone	26
c3: Check for hazards and damage	35
c4: Assess stairs/escalators	16
c5: Care about others	10

c6: Use stairs	63
c7: Use escalators	20
c8: Go to an assembly point	74
c9: Stay with the Doctor NPC at the main entrance	9

The correct way to interpret the diagrams is to move from one behavior to its following behavior in a single direction [41]. Although the diagrams show behavioral paths from the occurrence of an event, it does not mean that any or all participants conducted their behaviors entirely following the same paths. The frequencies in brackets indicate the frequencies of the occurrence of a transition rather than individual participants. In Figure 5, after noticing the impact of an earthquake, taking cover under a table (a1) is the first dominant behavior displayed which has a proportion of 0.89 with a frequency (n) of 74. One participant moved to the doorway to take cover; and another participant moved to a corner and took cover. These positions are not safe, and these behaviors are not recommended for earthquake safety. After taking cover, participants made four different behaviors. Caring about others (a7, 0.20, n = 16), checking for hazards and damage (a8, 0.20, n = 16), and moving other objects away such as chairs around them (a6, 0.15, n = 12) were more common than looking for the first aid kit (a9, 0.01, n = 1). When the earthquake dissipated (Figure 6), the majority of participants decided to check for hazards and damage (b1, 0.54, n = 45) as their first action in the meeting room, while some cared about others (b2, 0.24, n = 20), waited for further instructions (b4, 0.16, n = 13), or collected the mobile phone (b3, 0.06, n = 5) as their first action. After checking for hazards and damage (b1), the most frequent behaviors were unplugging the photocopier (b8, 0.20, n = 11) and caring about others (b2, 0.29, n = 16). Following caring about others (b2), common behaviors were collecting the mobile phone (b3, 0.26, n = 11) or checking for hazards and damage (b1, 0.19, n = 8). After picking up the mobile phone (b3), participants made a phone call (b9, 0.48, n = 10) or collected their keys (b10, 0.33, n = 7). When participants were ready to evacuate (Figure 7), over two-thirds decided to evacuate with the Doctor NPC (c1, 0.69, n = 57) while the rest decided to evacuate alone (c2, 0.31, n = 26). When following the Doctor NPC, it was more common that participants followed the Doctor NPC straight away to use the stairs (c6, 0.44, n = 25). However, some decided to check for hazards and damage (c3, 0.39, n = 22) as their first action when following the Doctor NPC. After checking for hazards and damage, the dominant behavior was to descend to the ground floor using the stairs (c6, 0.46, n = 16). Following the use of the stairs, the most common behavior was to go to an assembly point (c8, 0.87, n = 55). Similarly, after using escalators, the most common behavior was to go to an assembly point (c8, 0.95, n = 19).

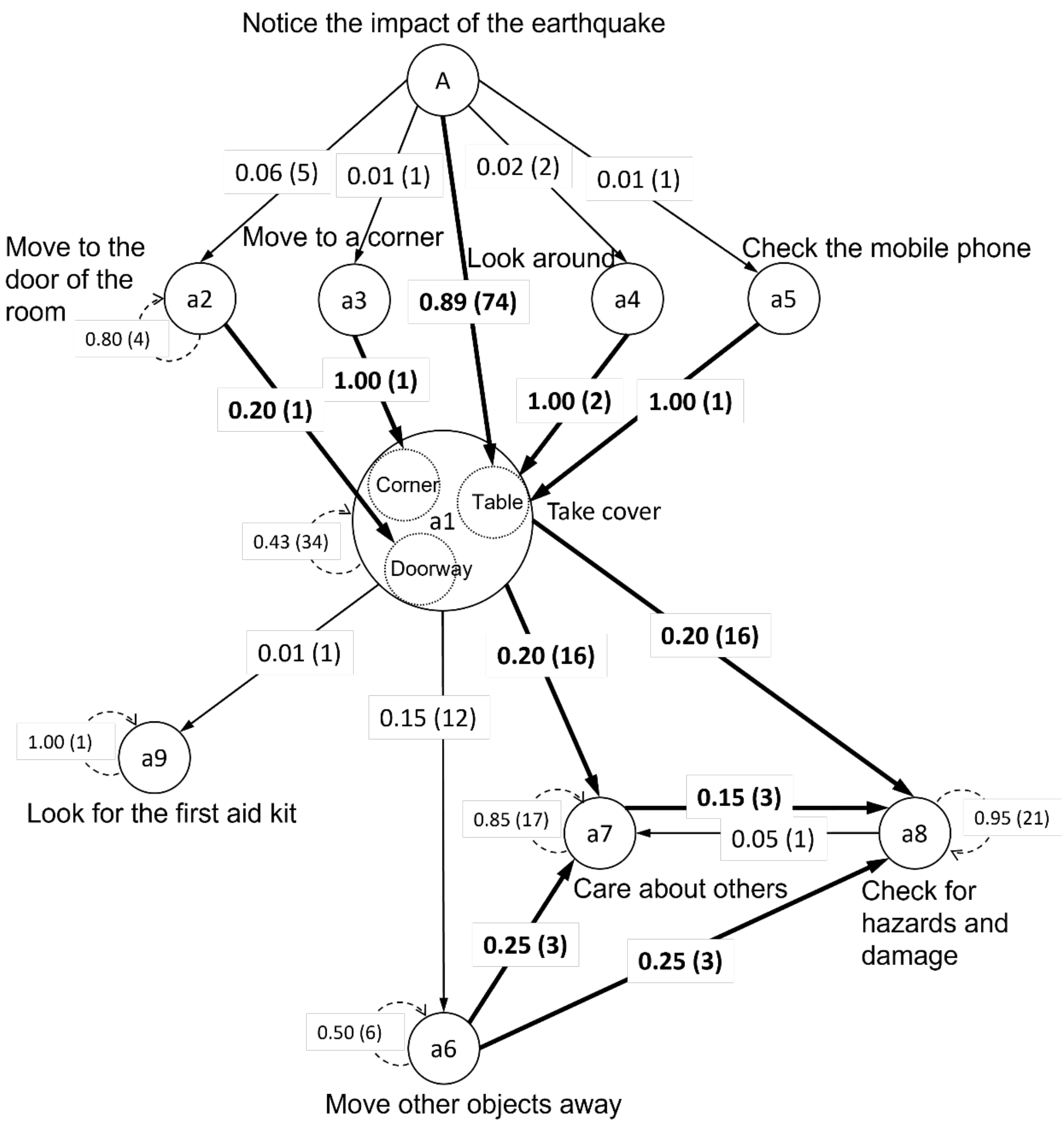

Figure 5 – The behavioral transition diagram of behaviors exhibited within the IVR scenario and verbal protocols for stage A (earthquake starts). Proportions are shown on arrows, followed by frequencies in brackets. Arrows with solid lines represent the directions of behavioral transitions. Returning arrows with dash lines mean the end of behavioral engagement in this stage. Bold lines highlight the most occurred transitions following a behavior. The positions of circles do not indicate temporal orders.

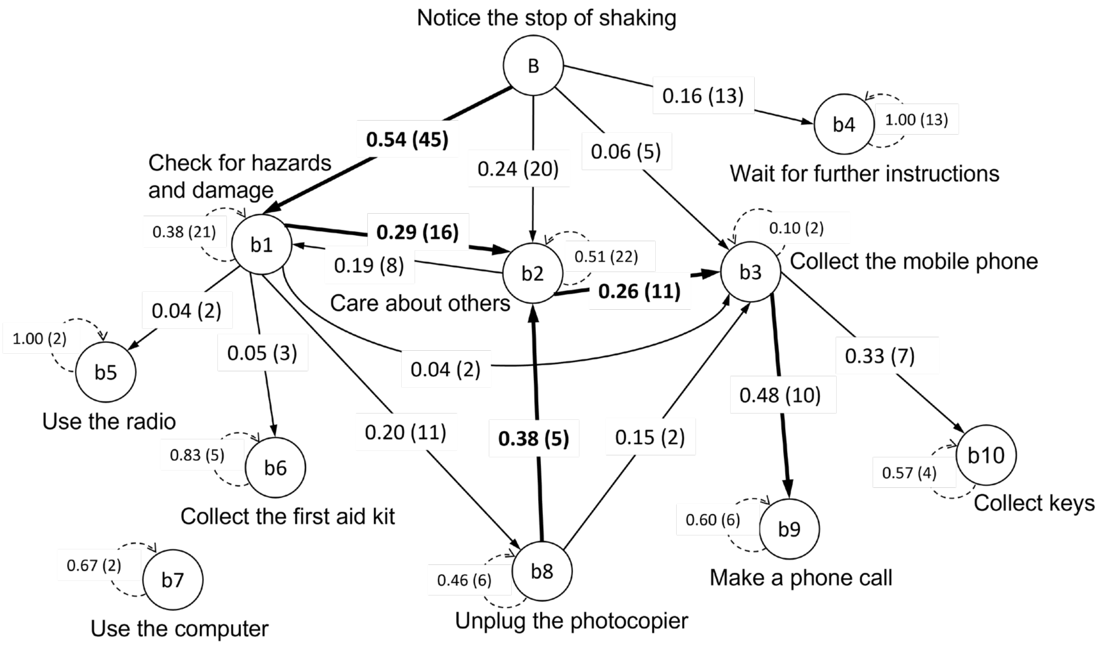

Figure 6 – The behavioral transition diagram of behaviors exhibited within the IVR scenario and verbal protocols for stage B (earthquake stops). Proportions are shown on arrows, followed by frequencies in brackets. Arrows with solid lines represent the directions of behavioral transitions. Returning arrows with dash lines mean the end of behavioral engagement in this stage. Bold lines highlight the most occurred transitions following a behavior. The positions of circles do not indicate temporal orders.

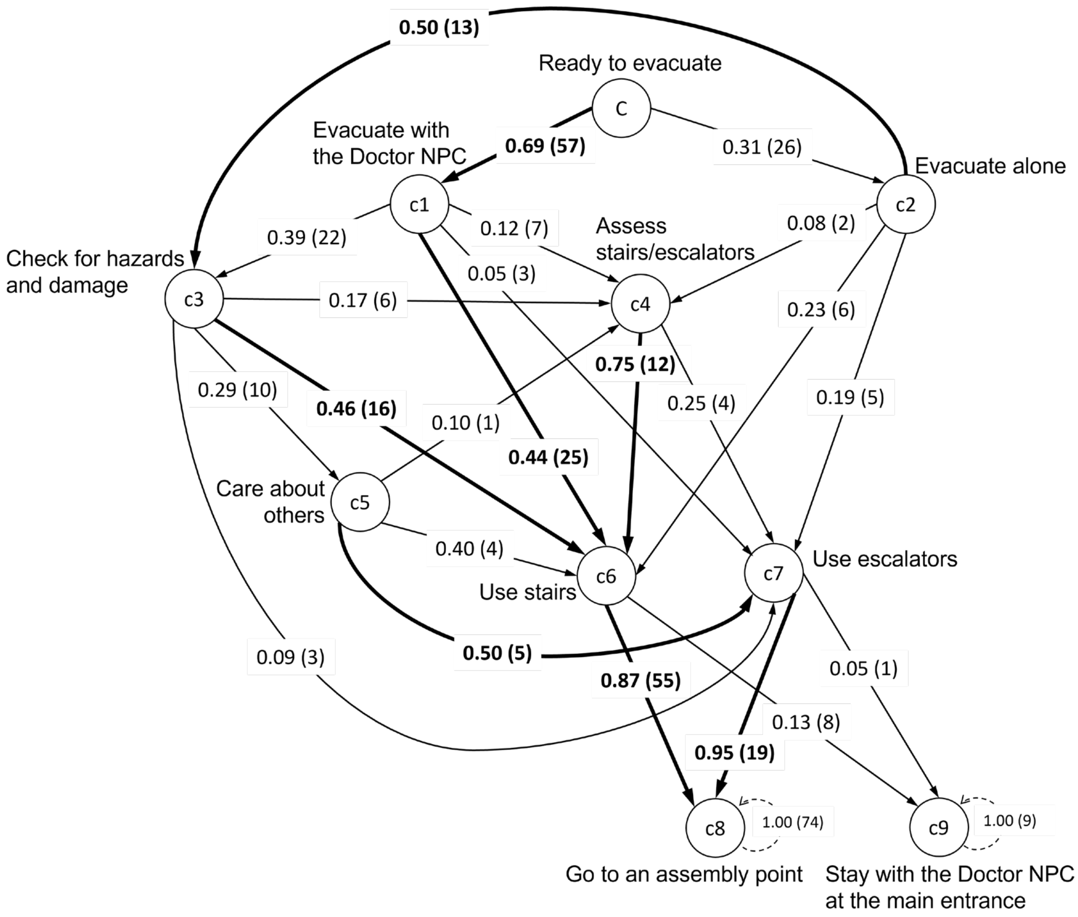

Figure 7 – The behavioral transition diagram of behaviors exhibited within the IVR scenario and verbal protocols for stage C (evacuation starts). Proportions are shown on arrows, followed by frequencies in brackets. Arrows with solid lines represent the directions of behavioral transitions. Returning arrows with dash lines mean the end of behavioral engagement in this stage. Bold lines highlight the most occurred transitions following a behavior. The positions of circles do not indicate temporal orders.

4.2 Behavioral paths

The behavioral transition diagrams give a clear picture of the likelihood of an action to be taken after the occurrence of a behavior in a particular event for a cohort of individuals. However, the diagrams cannot clearly identify the behavioral transition or behavioral path of an individual in an event. To provide this information, we apply a visual analytics approach to present behavioral paths, with color-coded squares representing induvial behaviors [82]. In a behavioral path, each behavior is represented by a unique color-coded square. For the same behaviors that occurred across three stages (e.g., care about others is numbered with a7, b2, and c5 in three stages), they were assigned with the same color codes. Consequently, a behavioral path is presented by color-coded squares in a contiguous sequence (see Figure 8, Figure 9, and Figure 10). Color-coded squares are organized in a vertical way to represent a behavioral path. Vertical grey bars and numbers indicate the number of participants who had the identical behavioral path (ordered from most to least common).

The figures display all the varieties of behavioral paths exhibited by participants. The correct way to interpret the figures is to read behavioral paths column by column. For instance, according to Figure 8, when an earthquake began, twenty-nine participants illustrated the identical behavioral path where only one action was taken: taking cover (a1). Another four participants were on the same behavioral path which has a single action again: trying to escape from the earthquake by moving to the door of the room (a2). These thirty-three participants did nothing else for the rest of the shaking stage. Some participants were on the behavioral path which has two actions in the shaking stage. For instance, after taking cover (a1), fifteen participants checked for hazards and damage (a8), thirteen participants cared about others (a7), six participants moved other objects away (a6), and one participant looked for the first aid kit (a9). There are also behavioral paths that consist of three behaviors in this stage. When the earthquake stopped, participants showed different types of behavioral paths before evacuating (Figure 9). Most of the participants demonstrated the behavioral paths that only has one action, including checking for hazards and damage (b1, seventeen participants), waiting for further instructions (b4, thirteen participants), and caring about others (b2, seven participants). The rest of the participants followed the behavioral paths that had two or more actions in this stage. When participants started evacuating the building (Figure 10), their behaviors fell into different behavioral paths. Twenty-five participants followed the same behavioral path. They first started evacuation with the Doctor NPC (c1), followed by using the stairs to descend to the ground floor (c6), and eventually went to an assembly point (c8). Another nine participants did one more action than those twenty-five participants, which was to check for hazards and damage (c8) before using the stairs (c6).

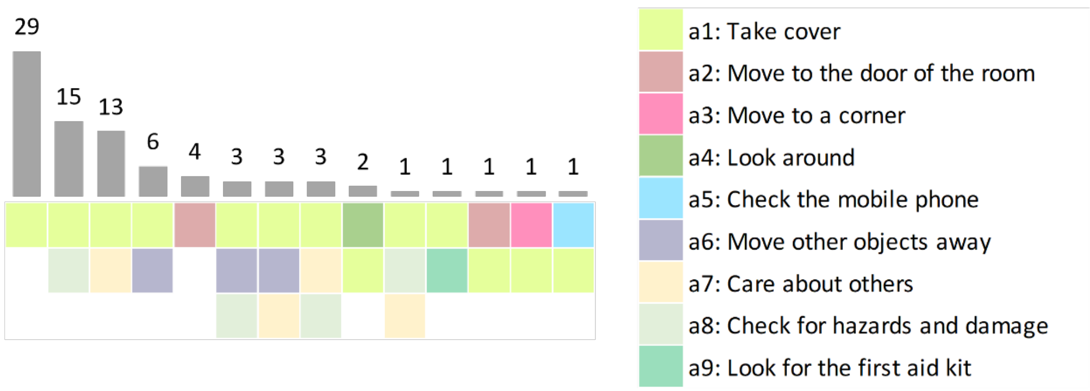

Figure 8 – The paths of behaviors exhibited within the IVR scenario and verbal protocols for stage A (earthquake starts). Color-coded squares are organized in a vertical way to represent a behavioral path. Vertical grey bars and numbers indicate the number of participants who had the identical behavioral

path (ordered from most to least common)

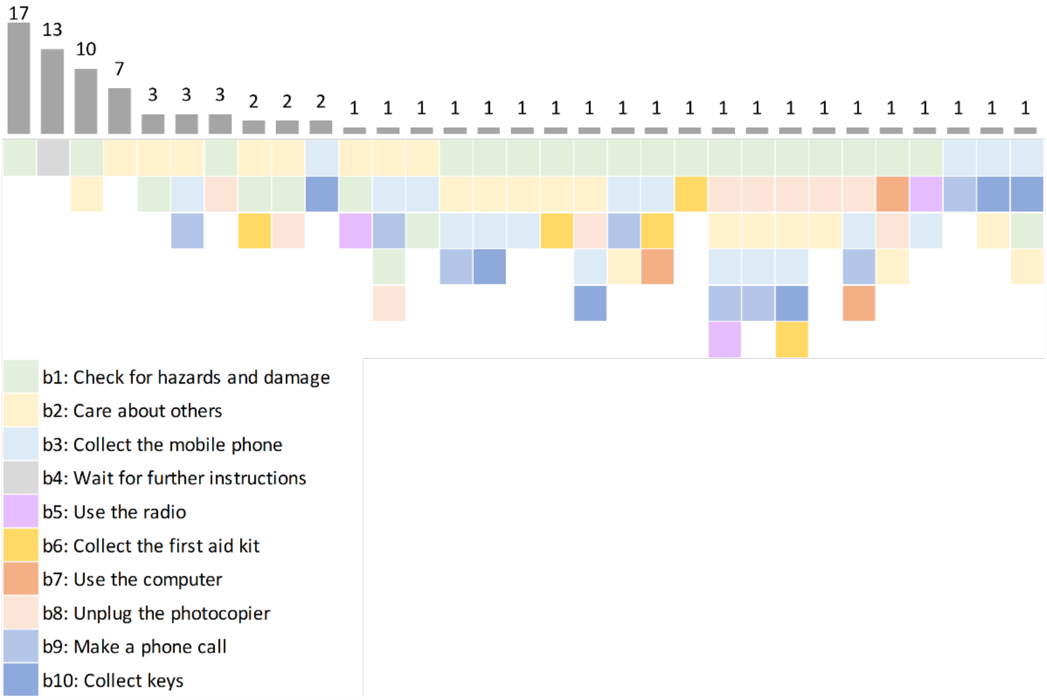

Figure 9 – The paths of behaviors exhibited within the IVR scenario and verbal protocols for stage B (earthquake stops). Color-coded squares are organized in a vertical way to represent a behavioral path. Vertical grey bars and numbers indicate the number of participants who had the identical behavioral path (ordered from most to least common)

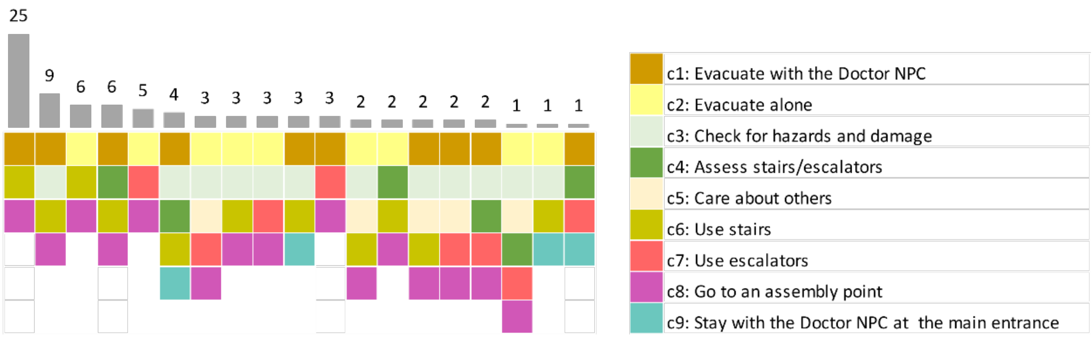

Figure 10 – The paths of behaviors exhibited within the IVR scenario and verbal protocols for stage C (evacuation starts). Color-coded squares are organized in a vertical way to represent a behavioral path. Vertical grey bars and numbers indicate the number of participants who had the identical behavioral path (ordered from most to least common)

5. Discussion

This study reveals some interesting implications. Firstly, the analysis of the sequence of early behaviors (during and immediately after an earthquake) reveals that people have strong motivations to check damage and help others; however, many may attempt this activity when self-protection is secured (e.g., after taking cover). This is analogous to the advice of airlines to improve the sequence of behaviors when cabin pressure drops: securing your own oxygen mask before helping others. This reveals the need for self-protection training and messaging to ensure people take cover before trying to help others or check for hazards. Lambie et al. [39] analyzed security video recordings captured the 22 February 2011 Christchurch earthquake event from the Christchurch Public Hospital. They found providing assistance to others contributes to 3.5% of total actions that occurred during the shaking, and 7.3% of total actions occurred immediately after the shaking. However, the sequence of this action was not analyzed, and they acknowledged 'many individuals exhibited more than one post-event behavioural response'. Similarly, Bernardini et al. [11] found that pro-social behaviors (i.e., oral and visual communication, and assistance to elderly and children) occurred in 54% of scenes (in pre-evacuation phases) from the video recordings of earthquakes in New Zealand, Italy, and Japan. The details of behavioral transitions and sequences are not shown in that study.

Secondly, the behavioral paths in stage B (immediately after the shaking stopped, before evacuation) show that many people do not realize the actions they can take to respond to post-earthquake scenarios (Figure 9). New Zealand Civil Defence gives over a dozen of recommended behavioral responses for what to do after an earthquake [83]; however, in our experiment, 45% of participants took only one action (i.e., caring about others or checking for hazards and damage) and 16% of participants did nothing but waited for further instructions. Only 7% of participants explored the meeting room and utilized the resources available to mitigate hazards and risk, performing over five actions in this stage, such as checking for hazards and damage, caring about others, unplugging the photocopier that was sparking, collecting the first aid kit, using the radio, or collecting personal mobile phone or keys. This finding is consistent with that of Feng et al. [84] who discovered that participants scored the least in the knowledge test for behavioral responses inside a building after an earthquake. Similarly, Lambie et al. [39] identified only a few behavioral responses in addition to checking for hazards and helping others immediately after the earthquake from video recordings, such as using phones (1.5%) and cleaning up (1.8%).

Lastly, the behavioral transition diagram in stage C (evacuation stage) reveal that participants who were evacuating alone were more likely to check for hazards and damage (50%) than participants who were evacuating with the Doctor NPC (39%) on their way out (Figure 7). This finding implies that authority figures may influence the decision-making and behavioral responses of people in emergencies. This phenomenon is common in real-world emergency cases [85-87]. People are more likely to follow and rely on authority figures in emergencies. However, this may lead to less autonomy of decision-making and awareness of surrounding situations. This compromise is also manifested in our results. Although there were people gathering in an assembly point (an open space) and the main entrance was not a safe place to stay, nine participants still decided to stay with the Doctor NPC close to the main entrance; among them, eight of them started evacuation following the Doctor NPC at the beginning (see the behavioral paths ending with c9 in Figure 10).

5.1 Limitations and future research

The present study has several limitations. Firstly, as discussed in Section 1, the gap between the real world and IVR simulations cannot be ignored. This limitation can be reflected in a few ways. For instance, the virtual objects in the IVR were not interactive. The interaction with such objects relied on limited controls and verbal protocols. In addition, the virtual objects and events were not fully inclusive. That is, participants could perform actions with only a limited set of objects and respond to preset events (e.g., a mobile phone, a set of keys, a photocopier that was sparking). Also, the behaviors of NPCs were modelled using preset scripts, and therefore they could not respond to participants. Response and feedback were absent in the interaction with NPCs as well. Earthquakes are dynamic phenomena during which a set of random events can take place. However, there was not the possibility to elicit behaviors related to other objects or events in the present study. Taken together, the gap between the real world and IVR is inherent as IVR is a type of laboratory settings, which leads to the lessening of ecological validity [36]. Future human-computer interaction research may look into enhancing the ecological validity of IVR. In addition, future research could investigate different types of buildings and participants, extending the external validity of the present study. Secondly, the Hawthorne effect might occur as participants were aware of the fact that their behaviors were observed and recorded. As a result, participants were more likely to exhibit pro-social and altruistic behaviors [88-91]. This limitation is inherent to the experimental approach as verbal protocols were collected concurrently [67]. Thirdly, some minor behaviors were omitted in the behavioral transition diagrams (e.g., Figure 6 does not include the behavioral transitions with a frequency of one) to increase the diagrams' readability. Although this is a common practice in BSA [40,41], it still jeopardizes the completeness of information. Future research could explore different strategies to demonstrate complete behavioral transition diagrams. Fourthly, as demonstrated in this study, participants could take cues from others during decision-making; and especially, authority figures play an influential role for others in emergencies. The behaviors illustrated by the Doctor NPC and Visitor NPC could influence the actions taken by participants. For instance, at the beginning of an earthquake, the proportion of participants who took cover can be different if both NPCs did not choose to take cover. This limitation may affect the counts and percentages demonstrated in the behavioral transition diagrams and behavioral paths. Lastly, prior knowledge and experience can affect experiment results. In the present study, the self-reported awareness of and preparedness for appropriate behavioral responses from participants reached a score of 0.57 (Figure 4), showing that participants did not have an adequate understanding of appropriate behavioral responses. This is reflected in the results where many participants did not realize their actions to respond to post-earthquake scenarios (Figure 9). The behavioral transition diagrams and behavioral paths illustrated in this study are applicable to the population with similar levels of knowledge and preparedness for earthquakes. The results may change if people are well or less prepared for earthquakes.

Future research can address the limitations of the present study. Firstly, as people can take cues from others in emergencies, future studies can investigate the interaction between participants and NPCs. Comparative studies can be conducted where NPCs illustrate alternative behaviors in the same emergency scenario. It could be interesting to observe different behavioral transition diagrams and behavioral paths from participants. Secondly, behavioral differences exist among different age groups and sex groups. For instance, in stage A (earthquake starts), 80.0% of participants (20) aged 20 to 29 took cover and following this, 32.0% of them (8) exhibited additional actions. While for participants aged 30 to 39, 96.0% (24) took cover, and 56.0% (14) took further actions. This result shows that participants aged 30 to 39 might have more knowledge and experience about earthquakes than those aged 20 to 29. Also, in stage A (earthquake starts), 94.7% of females (36) took cover and following this, 34.2% of females (13) exhibited additional actions. For males, 84.4% (38) took cover, and 51.1% (23) took further actions in this stage. However, this study does not conduct BSA to generate behavioral transition diagrams and behavioral paths based on the age, sex, or other characteristics of participants. Canter et al. [48] proposed different behavioral transition diagrams for both males and females in domestic fires. Future research can follow this direction to extend BSA for behavioral responses in earthquakes based on individual characteristics, such as age or sex. Thirdly, this study does not investigate the effects of prior knowledge and experience on behavioral sequences. Some participants never experienced fire drills or earthquake drills (Table 2). In stage A (earthquake starts), 88.4% of participants (61) who never experienced earthquake drills before decided to take cover and 42.0% (29) took further actions after being covered. More proportions of the others who had experience with earthquake drills exhibited appropriate behavioral responses, where 92.9% (13) took cover, and 50.0% (7) took further actions. This result suggests that participants who experienced earthquake drills before could be more knowledgeable about the appropriate behavioral responses to earthquakes than those who never did earthquake drills. This study does not conduct BSA to generate behavioral transition diagrams and behavioral paths based on prior knowledge and experience. Future research can look into this aspect and examine the correlation between prior knowledge and behavioral sequences. Fourthly, regarding evacuation and safety aspects, future research could apply a similar methodology to investigate other types of emergencies, such as fire, active shooting, or tsunami. Lastly, the BSA in the present study also reveals some interesting aspects for future earthquake safety training. For instance, it is essential to highlight that self-protection is the most critical behavior when doing other activities during and after an earthquake. Furthermore, people need to understand it is still essential to stay alert and maintain autonomous decision-making when following authority figures. However, this may bring conflictive decisions, which would need further investigation.

6. Conclusions

The integration of IVR and VPA is an alternative solution to investigate human behaviors under extreme conditions safely. In the present study, a virtual earthquake drill was conducted in IVR to produce insights into behavioral responses in earthquakes and post-earthquake evacuation. VPA was applied to make the reasoning processes of participants explicit. In addition, the present study implemented BSA to cast light on the behavioral patterns in earthquake emergencies, contributing to the knowledge domain of earthquake evacuation. As an effective visual analytics approach to behavioral analysis, BSA was implemented to generate a clear visual presentation of behavioral patterns.

Results were reported in the three stages of an earthquake emergency, showing a variety of behavioral patterns. The results reveal that with the notice of the impact of the earthquake, most participants decided to take cover first. After securing self-protection, they started to assess the situations and care about others around them. When the earthquake stopped, many participants did not realize exploring their surroundings or utilizing resources to mitigate hazards and risks before evacuation. When the evacuation started, many participants tended to follow the Doctor NPC and hand over decision-making to the Doctor NPC. Only a few stayed alert and kept assessing the surroundings on their way out.

This study demonstrates a complete set of behavioral data in an earthquake emergency. The richness of behavioral information and dynamic relationships within behaviors are beneficial to giving insights into the course of behaviors that taken place across an entire earthquake emergency. Our results expose the decision-making order during an earthquake, the lack of understanding of behavioral responses after an earthquake, and the reliance on authority figures in post-earthquake evacuation. These findings will be useful for future investigation on behavioral responses in emergencies and guidance on training programs.

Acknowledgements

This research has been funded by the MBIE-Natural Hazards Research Platform (New Zealand), Grant Number: C05X0907.

Supplementary Material 1

Transition matrices for stage A (earthquake starts)

Antecedents	Sequiturs	Proportions	Frequencies
Notice the impact of the earthquake	Take cover (under a table)	89%	74
Notice the impact of the earthquake	Move to the door of the room	6%	5
Notice the impact of the earthquake	Look around	2%	2
Notice the impact of the earthquake	Move to a corner	1%	1
Notice the impact of the earthquake	Check the mobile phone	1%	1
Take cover	Move other objects away	15%	12
Take cover	Check for hazards and damage	20%	16
Take cover	Care about others	20%	16
Take cover	Look for the first aid kit	1%	1
Move to the door of the room	Take cover (under a doorway)	20%	1
Look around	Take cover	100%	2
Move to a corner	Take cover (at a corner)	100%	1
Check the mobile phone	Take cover	100%	1
Move other objects away	Check for hazards and damage	25%	3
Move other objects away	Care about others	25%	3
Check for hazards and damage	Care about others	5%	1
Care about others	Check for hazards and damage	15%	3
Take cover	End of behavioral engagement	43%	34
Move to the door of the room	End of behavioral engagement	80%	4
Check for hazards and damage	End of behavioral engagement	95%	21
Care about others	End of behavioral engagement	85%	17
Move other objects away	End of behavioral engagement	50%	6
Look for the first aid kit	End of behavioral engagement	100%	1

Transition matrices for stage B (earthquake stops)

Antecedents	Sequiturs	Proportions	Frequencies
Notice the stop of shaking	Check for hazards and damage	54%	45
Notice the stop of shaking	Care about others	24%	20
Notice the stop of shaking	Collect the mobile phone	6%	5
Notice the stop of shaking	Wait for further instructions	16%	13
Check for hazards and damage	Care about others	29%	16
Check for hazards and damage	Collect the mobile phone	4%	2
Check for hazards and damage	Collect the first aid kit	5%	3
Check for hazards and damage	Unplug the photocopier	20%	11
Check for hazards and damage	Use the computer	2%	1
Check for hazards and damage	Use the radio	4%	2
Care about others	Check for hazards and damage	19%	8
Care about others	Collect the mobile phone	26%	11
Care about others	Collect the first aid kit	2%	1
Care about others	Unplug the photocopier	2%	1
Collect the mobile phone	Make a phone call	48%	10
Collect the mobile phone	Collect keys	33%	7
Collect the mobile phone	Check for hazards and damage	5%	1
Collect the mobile phone	Collect the first aid kit	5%	1
Unplug the photocopier	Care about others	38%	5
Unplug the photocopier	Collect the mobile phone	15%	2
Make a phone call	Check for hazards and damage	10%	1
Make a phone call	Use the radio	10%	1
Make a phone call	Use the computer	10%	1
Make a phone call	Care about others	10%	1
Collect keys	Collect the first aid kit	14%	1
Collect keys	Care about others	14%	1
Collect keys	Check for hazards and damage	14%	1
Collect the first aid kit	Use the computer	17%	1
Use the computer	Unplug the photocopier	33%	1
Use the radio	Collect the mobile phone	33%	1
Check for hazards and damage	End of behavioral engagement	38%	21
Care about others	End of behavioral engagement	51%	22

Collect the mobile phone	End of behavioral engagement	10%	2
Wait for further instructions	End of behavioral engagement	100%	13
Unplug the photocopier	End of behavioral engagement	46%	6
Make a phone call	End of behavioral engagement	60%	6
Collect keys	End of behavioral engagement	57%	4
Collect the first aid kit	End of behavioral engagement	83%	5
Use the computer	End of behavioral engagement	67%	2
Use the radio	End of behavioral engagement	67%	2

Transition matrices for stage C (evacuation starts)

Antecedents	Sequiturs	Proportions	Frequencies
Ready to evacuate	Evacuate alone	31%	26
Ready to evacuate	Evacuate with the Doctor NPC	69%	57
Evacuate alone	Check for hazards and damage	50%	13
Evacuate alone	Assess stairs/escalators	8%	2
Evacuate alone	Use stairs	23%	6
Evacuate alone	Use escalators	19%	5
Evacuate with the Doctor NPC	Check for hazards and damage	39%	22
Evacuate with the Doctor NPC	Assess stairs/escalators	12%	7
Evacuate with the Doctor NPC	Use stairs	44%	25
Evacuate with the Doctor NPC	Use escalators	5%	3
Check for hazards and damage	Care about others	29%	10
Check for hazards and damage	Assess stairs/escalators	17%	6
Check for hazards and damage	Use escalators	9%	3
Check for hazards and damage	Use stairs	46%	16
Assess stairs/escalators	Use stairs	75%	12
Assess stairs/escalators	Use escalators	25%	4
Care about others	Assess stairs/escalators	10%	1
Care about others	Use stairs	40%	4
Care about others	Use escalators	50%	5
Use stairs	Go to an assembly point	87%	55
Use stairs	Stay with the Doctor NPC at main entrance	13%	8
Use escalators	Go to an assembly point	95%	19

Use escalators	Stay with the Doctor NPC at main entrance	5%	1
Go to an assembly point	End of behavioral engagement	100%	74
Stay with the Doctor NPC at main entrance	End of behavioral engagement	100%	9

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A sequence analysis of behaviors in immersive virtual reality for indoor earthquake and post-earthquake evacuation

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2022-06-01