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Comparison of Emergency Response Abilities and Evacuation Performance Involving Vulnerable Occupants in Building Fire Situations

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Abstract: The mobility impaired, the deaf or hard of hearing, the blind or visually impaired, the cognitively impaired, and the elderly population are among several examples of groups categorized as particularly vulnerable to fire-related hazards. Given the severity of the threat that building fires pose for these vulnerable groups in terms of the different types of debilitation they experience, it is crucial to distinguish the respective attributes of each group and map out how such differences lead to differing performance levels during fire evacuations. To better gauge each group's capacity to cope with building fires, this study collected survey data from social service providers and staff members who provide care for vulnerable healthcare facility residents. The questionnaires were designed to assess each group's emergency response abilities and render them in quantifiable form in terms of perception, interpretation, decision-making, and mobility. The results of the survey serve as the input values for an evacuation simulation model which analyzes the evacuation performances (i.e., response and movement time) of vulnerable groups. The study concludes by proposing managerial strategies for the enhancement of fire safety in healthcare facilities on the basis of outcome analysis. Understanding the evacuation characteristics of disabled and vulnerable groups is expected to provide a foundation for the safety managers and staff members of relevant facilities to prepare for and deal with unexpected emergencies in an efficient and effective manner.

Keywords: building fire; high risk groups; evacuation characteristics; vulnerable population

1. Introduction

The consequences of an unexpected building emergency can include a higher fatality rate when the facility in question is filled with vulnerable occupants. Vulnerable occupants refer to those more susceptible to the negative effects of high-danger situations due to their limited capacity to adapt to the hazards that occur during evacuation procedures [1]. In the context of building fires, groups such as the mobility impaired, the deaf or hard of hearing, the blind or visually impaired, and the cognitively impaired are categorized as those that experience increased fire risks [2,3]. The elderly population, in particular, constitutes the most vulnerable group when evacuating from building fires because persons more advanced in years often experience complications due to low mobility, distortion of or confusion in situational perception, hearing and vision impairment, and problems with retaining focus over



a sustained period of time [3,4]. Statistics show that the average fire-related death rate per million people in the U.S. was 26.7 for adults over the age of 65 in 2016, whereas the national fire-related death rate during the same time period was much lower at 10.9 [5]. Similarly, population groups that are not as advanced in age but have hearing, vision, or mobility impairment may be at a disadvantage during fire emergencies due to constraints on their ability to detect or escape from the fire itself or from fire-related hazards [2]. In addition, people with cognitive disabilities often have comparable difficulty interpreting emergency situations and making the decisions necessary to complete a safe evacuation.

There has been a continuous increase in the percentage of the population taken up by groups vulnerable to fire-related events. Official projections foresee that individuals 65 years and above will comprise 12 percent of the total world population (equal to 1 billion people) by 2030, with that number increasing to more than 1.6 billion by 2050 [6]. Because these demographical trends, most countries are either preparing for or already undergoing the effects of an aging population due to improvements in life expectancy coinciding with a declining birth rate. Furthermore, approximately 15% of the world's population has some form of disability, whereas acquired disabilities are also more likely to increase under the influence of age and chronic health conditions [7].

The upsurge of vulnerable groups in the overall population has led to a corresponding expansion of the health care industry. Although many of these healthcare facilities provide relatively safe and comfortable care for people in need of professional assistance, their occupants may be left exposed to critical threat levels during fire emergencies due to disability and age-related limitations. Even if the facilities in question have social service providers or members of staff on call within the building, they will also have a much higher than average number of occupants unable to evacuate themselves in the event of a fire outbreak [8,9]. Moreover, evacuation ability varies among the individual occupants of a healthcare facility depending on the extent to which they are physically and mentally prepared to handle the challenges of a fire-related emergency. For example, someone who is hearing impaired may become aware of a fire situation much later than someone who is not because he or she cannot respond to the fire alarm. Disabilities also impede the processes that follow the realization that a fire may have broken out in the building, as each occupant must be able to find a way out of the facility and follow it in order to succeed in his or her evacuation. In the case of a person using crutches, however, it would be nearly impossible for him or her to exit the building unassisted and in time even if the person had been successfully alerted to the fire emergency through the fire alarm. Under such circumstances, it is crucial to distinguish the respective attributes of each vulnerable group during emergencies and thereby enhance evacuation performance in fire situations. Understanding these characteristics is expected to provide a foundation for the safety managers and staff members of relevant facilities to more efficiently prepare for and deal with unexpected emergencies threatening the safety of vulnerable occupants.

The foremost aim of this study was to understand the range of variability in the evacuation characteristics of different vulnerable groups attempting to exit a healthcare facility during fire-related emergencies. Vulnerable occupants, in this instance, were divided into five high-risk groups: the elderly, those with limited mobility, those with vision impairment, those with hearing impairment, and those with cognitive disabilities. To better gauge each group's capacity to cope with building fires, the study collected survey data from social service providers and staff members who care for vulnerable healthcare facility residents. The questionnaires were designed to investigate each group's emergency response abilities and render them in quantifiable form in terms of perception, interpretation, decision-making, and mobility. The results of the survey serve as the input values for an evacuation simulation model that analyzes the evacuation performances (i.e., response and movement time) of vulnerable groups. The study concludes by proposing managerial strategies for the enhancement of fire safety in healthcare facilities on the basis of outcome analysis and model application in a variety of scenarios.

2. Literature Review

2.1. Risk Factors to the Vulnerable Population during Fire Exposure

In a building fire, the actions of its occupants are not based on random chance shaped by a shifting environment but are instead the result of individual behavioral or decision-making processes [10,11]. Prior research on this topic indicates that the progression of behavior involved in the response to an emergency situation includes stages such as (1) perception of certain cues, (2) interpretation of the situation and its consequent risks based on perceived cues, (3) decision-making in terms of subsequent action according to the interpretation of the situation, and (4) performance of the finalized action [11–16]. More specifically, the phases that precede formulating an evacuation decision (e.g., information seeking, response) are also known as the risk perception process, as they are closely associated with the extent of the risk that the occupants of a particular facility perceive on the basis of observing the situation around them [17,18]. Because of the processes involved in building fire evacuations, physical or cognitive disabilities among the occupants would not only have an effect on their ability to respond to and evacuate from an emergency situation but would also exhibit a much more significant impact than they might under non-threatening circumstances [19].

Once a building fire breaks out, the common assumption is that the individuals experiencing it will consistently see, hear, smell, or otherwise use their senses to respond to the external and social cues in their environment [11,20]. Limited perception due to visual, auditory, or cognitive impairment can result in a failure to recognize crucial fire-related cues (e.g., smoke, fire alarms, vocal or gesture-based communication, general egress behavior), and the disruption of an evacuee's attempt to take the necessary steps toward interpreting the situation at hand and forming the appropriate strategies to deal with the risks that he or she might encounter while vacating the premises [21]. Being unable to perceive the state of a building would prevent occupants from remaining aware of rapidly occurring changes in the immediate environment and moving on to the phase of their evacuation, which requires interpretation and decision-making concerning possible danger situations ahead [11,22,23].

During the phase entailing interpretation of the situation and the risk involved, building evacuees must attempt to make inferences based on the cues obtained in the previous stage of the evacuation process [23–26]. Interpretation here includes organizing perceived cues within a framework [23], finding meaning from cues in relation to the current outcome [23], and/or understanding a situation by imagining how events are unfolding [11,27,28]. Failure to perceive the right cues, in addition to the effects of various illnesses or cognitive dysfunctions, can have substantial ramifications for successfully completing evacuation processes [29]. The most common obstacles to situational risk perception include cognitive disabilities and, in the case of older adults, dementia, making it either difficult or impossible to perform a quick and accurate evaluation of one's surroundings even if the evacuee does not have any other disabilities [29].

The third phase in the evacuation process entails making decisions as to what steps the evacuee may take next according to his or her interpretation of the situation and its risks, and will likewise be directly influenced by certain limitations to an individual's abilities [26]. Thus, any delay in accurately perceiving and understanding the urgency of the situation would create setbacks in time taken to arrive at an evacuation decision and increase time needed to form a response, as reducing both are critical elements in a safe and prompt evacuation [11].

As soon as a building occupant makes the decision to exit the facility, he or she begins the last stage of the behavioral process and carries out the finalized action on the basis of the decisions that have been made at earlier points in the evacuation [26]. This is also the stage during which an individual's ability to move to a target exit constitutes a critical factor in whether or not he or she can reach a place of safety before building conditions become overly unstable. However, an evacuee with a disability that affects mobility will move at a much slower pace than a non-disabled evacuee if the disabled evacuee is proceeding to an exit independently, with or without a walking aid [29]. Many of the elderly occupants in healthcare facilities, for instance, use wheelchairs, which hinder quick reactions to a fire threat. In some cases, an outright loss of mobility could cause an evacuee to be completely reliant on the assistance of a non-disabled person in order to reach a safety zone [8,29].

2.2. Evacuation Behaviors in Vulnerable Populations

A considerable body of research across multiple fields has been devoted to analyzing the human response to unexpected fire situations. Canter (1980) classifies the various human behaviors observable during a fire evacuation into five sequential categories: (1) preparation before a fire, (2) recognition of a fire after the occurrence, (3) actions during the fire, (4) escape from the fire, and (5) the after-effects of the fire experience [30]. Due to their direct impact on evacuee safety, the second to fourth stages—recognition of a fire, actions during the fire, and escape from the fire—are the frequent focus of analysis in approaches such post-survey/interview and simulation. In order to understand how people recognize fire situations, researchers have often turned to the cognitive and social aspects of human behavior, including risk perception, decision-making, social influence, and group forming [18,31–34]. These findings emphasize that perceiving and interpreting a fire risk based on cues gathered from the surrounding environment (e.g., fire alarms, smoke, other people in the vicinity) plays a significant role in determining the appropriate time to initiate the actual evacuation sequence. In addition, prior studies also confirm that learning how people perceive, interpret, and utilize the information provided by signage systems is an important component of minimizing evacuation time [35–38].

Although such results highlight the role of human perception and interpretation during an evacuation, they tend to overlook how disabilities in perception and interpretation affect individual evacuation characteristics. Moreover, the majority of existing research on evacuation processes studies evacuee movement in real or virtual settings on the basis that subjects are without disabilities. Although this provides meaningful datasets for horizontal/vertical evacuation speed and evacuation flow rate across various scenarios, it would be largely inapplicable to circumstances that require an understanding of movement characteristics pertaining to different types of vulnerable groups (i.e., the elderly, those with mobility impairment, those with vision impairment, those with hearing impairment, and those with cognitive disabilities).

3. Method

3.1. Emergency Response Abilities among Vulnerable Evacuees

The study first conducted a survey to assess emergency response abilities in five vulnerable groups—the elderly, people with vision impairment, people with hearing impairment, people with mobility impairment, and people with cognitive impairment—placing emphasis on how their perception, interpretation, decision-making, and mobility differs from that of non-disabled persons.

3.1.1. Participants

The study used purposive sampling for its advantages in enabling case selection based on population characteristics best suited to the established research goals [39,40]. In keeping with the objectives of the study, the survey respondents were selected from a pool of practitioners employed at daily or long-term healthcare facilities, collecting data from those able to observe the abilities and behaviors of vulnerable occupants rather than from the vulnerable occupants themselves. This choice was made due to the fact that many of the vulnerable occupants would have had difficulty completing an objective assessment of their own evacuation abilities in comparison to a reference group.

The data for this study was collected in 2015 from healthcare providers at 10 different South Korean health care facilities for the elderly and for people with impaired vision, mobility, cognition, and hearing. The respondent affiliations for the 178 valid results are summarized in Table 1. Most of the respondents were employees at healthcare centers for the elderly (41.01%), whereas the remaining respondents worked at healthcare centers for the cognitively impaired (17.42%), the mobility impaired (15.73%), the hearing impaired (13.48%), and the vision impaired (12.36%). A total of 36.52% of the

respondents were male and 63.48% were female. Approximately 16.29% were between the ages of 20 and 29, 34.27% were between the ages of 30 and 39, 23.60% were between the ages of 40 and 49, 22.47% were between the ages of 50 and 59, and 3.37% were older than 60. As shown in Table 2, the respondents had varying years of experience in healthcare services, ranging between less than 2 years and more than 10 years.

Type of Healthcare Facility	% of Total Response
Healthcare center for the elderly	41.01
Healthcare center for the cognitively impaired	17.42
Healthcare center for the mobility impaired	15.73
Healthcare center for the hearing impaired	13.48
Healthcare center for the vision impaired	12.36

Table 1. Respondent affiliations.

Table 2.	Year of experience	as a healthcare	service provider.

Years of Experience in Healthcare	% of Total Response
Less than 2 years	19.66
Between 2 to 4 years	17.42
Between 4 to 6 years	18.54
Between 6 to 8 years	10.67
Between 8 to 10 years	8.43
More than 10 years	25.28

3.1.2. Material

The 14-question survey used in this study was designed to determine emergency response abilities in five different vulnerable groups. Each questionnaire was completed in person. The first section of the questionnaire gathered background information on the respondents, such as gender, age, the type of healthcare facility by which he or she was employed, the disabilities of the major occupants in his or her facility, his or her role as part of the facility staff, and the total number of years that he or she had worked as a healthcare service provider. The next section covered topics associated with a vulnerable occupants' emergency response abilities during unexpected fire situations. The first question asked the respondents to identify the most likely reason for a case of evacuation failure during a fire and was followed by questions on specific emergency response abilities. The questions took into account the fact that cognitive functions such as perception, interpretation, and decision-making serve as the foundation for learning, understanding, and dealing with emergency situations [41]. Functional limitations in speech, vision, and hearing have the potential to interfere with how people pick up on verbal announcements, read informative signs, or understand and decide how to exit a building [41]. The questions on the survey also considered the issue of mobility, which, in the case of a vulnerable occupant's ability to move to a place of a safety, falls into three groups: evacuating without any support, evacuate with support (e.g., walking canes, crutches, or wheel-chairs), and being incapable of independent movement and requiring the help of others to evacuate [19]. On the basis of the functions needed to complete the behavioral processes behind a successful evacuation, the items for evacuation response ability were designed, as summarized in Table 3, and presented to respondents in the form of questions such as, "What do you think would be the most critical reason for a vulnerable group failing to perform a successful evacuation?", "How would you rate a vulnerable group's ability to perceive fire-related cues during an emergency?", and "How would you rate a vulnerable group's ability to perform a self-evacuation in the event of a fire emergency?" In order to convert each vulnerable group's

evacuation response abilities into more quantifiable measures, the respondents were asked to rate each item for the vulnerable group that he or she was predominantly familiar with on a scale of 0–10, assuming that the evacuation response abilities of a non-disabled reference group would amount to a rating of 10.

Category	Evacuation Ability		
Perception	Ability to perceive fire-related cues or building signage		
Interpretation	Ability to understand perceived cues		
Decision-making	Ability to make the decision to evacuate and choose an available path		
	Ability to evacuate without any support		
Mobility	Ability to evacuate with support		
	Ability to evacuate with assistance from staff		

Table 3. Questionnaire items to gauge evacuation response ability.

3.2. Evacuation Performance among Vulnerable Occupants

On the basis of data analysis of the evacuation abilities of each vulnerable group, the study conducted evacuation simulations using a computational model previously developed and tested by the authors [42], thereby comparing evacuation performance results in terms of response and movement under different conditions. The simulation model was built using AnyLogic 7 software, which was developed by AnyLogic Company. The software provides a pedestrian library, which uses a social force model that allows individuals to move according to the pre-assigned rules in the given environment [43]. An example of a screenshot during the simulation is presented in Figure 1.



Figure 1. Screenshot during evacuation simulation.

3.2.1. Model Description

The evacuation model translated the survey results on evacuation ability into data on evacuation behavior and performance, including time required for each vulnerable group to make an evacuation

decision (i.e., response time) and exit the building (i.e., movement time) in a variety of evacuation conditions. The study opted for an agent-based modeling approach to simulating evacuation behavior, enabling the representation of autonomous agents with perception, interpretation, and decision-making abilities. Figure 2 illustrates the overall process of an agent's behavior with regard to the critical elements that affect his or her evacuation performance. A more detailed description of this process and the associated variables for the three critical elements—(1) perceived risk, (2) wayfinding ability, and (3) evacuation velocity—will be provided in the subsequent section.



Figure 2. Modeled process and factors in agent behavior.

At the sound of the initial fire alarm, each agent initiates an assessment of situational risk or establishes perceived risk (1 in Figure 1). The process of establishing an individual's perceived risk, which is the result of running through a risk perception sequence, functions as a critical factor in predicting the time needed for a building occupant to arrive at an evacuation decision [19,44,45]. The higher the level of perceived risk, the more quickly evacuees engage in protective action such as evacuation decisions [18,32,44–48]. On the other hand, when perceived risk is lower than the threshold which leads to an evacuation decision, evacuees may exhibit passive behavior by pretending that the situation is non-threatening [18,32,49,50] or searching for additional information about possible emergency situations [14,16,22,32,51,52]. These findings suggest that perceived risk is directly associated with the response time of each individual agent in the evacuation model.

Once an agent makes the decision to evacuate, his or her movement time is affected by exit/route selection (2 in Figure 1) and velocity (3 in Figure 1). Although familiarity with the layout of the building has no effect on whether or not a person attempts to leave the building immediately, it does influence the time that it takes for evacuees to locate the routes and exits available to them [53]. In addition, being able to perceive and interpret informative evacuation signage helps building occupants find the nearest route and exit for egressing the building.

During an actual evacuation, the velocity of the evacuees is affected not only by mobility but also by the level of risk that each individual perceives [42]. For example, a person would walk out of a building at a leisurely pace if he or she considered the situation to be relatively secure [42,54]. However, the same person would likely accelerate his or her exit from the building to maximum speed if the situation were to become life-threatening and if the amount of stress caused by those threatening conditions were to exceed a certain threshold value [54]. Therefore, the central mechanism of the model used in this study stipulated that changes in an agent's level of perceived risk would affect his

or her decision-making and trigger behavioral changes that encompass normal (i.e., not responding to emergency cues) and investigating (i.e., searching for additional information about possible emergency situations) approaches before the evacuation decision has been finalized and evacuating at walking speed (i.e., moving toward an exit at walking speed), and evacuating at accelerated speed (i.e., moving toward an exit at maximum speed) after the evacuation decision has been finalized [32,42,44,46]. Because individual levels of perceived risk operate on an arbitrary scale [46], the model assumes that perceiving no risk in a situation (i.e., normal state) represents value 0 and a perceived risk greater than thresholds 1, 2, and 3 would cause an agent to move on to the ensuing behavioral states of investigating, evacuating at walking speed, and evacuating at accelerated speed [42].

3.2.2. Model Variables

As previously stated, the critical elements that affect an individual agent's evacuation behavior and performance include (1) perceived risk, (2) wayfinding ability, and (3) evacuation velocity. Figure 3 illustrates how each element is affected by the agent's cognitive abilities and mobility within the model.



Figure 3. Influence of cognitive ability and mobility on evacuation performance.

The first element, perceived risk, is established as a result of the perception of fire-related cues, the interpretation of these cues and their meaning, the assessment of situational risk, and decision-making based on behavioral state [18,32,42,44,46]. The model for this study considers smoke, fire alarms, and the behavior of other people to be fire-related cues that an individual agent may perceive and interpret during an evacuation [18,42]. Recognizing indirect fire cues such as fire alarms or other people demonstrating protective behavior has a prolonged effect on shifting individual levels of perceived risk [18,32,42,44,46]. For instance, repeatedly seeing people perform a more active response to the emergency at hand (e.g., running toward an exit) than one's own response (e.g., investigating the situation) would increase one's perception of the risks involved in the situation [42,44,46]. However, being surrounded by passive responders (e.g., people continuing to engage in their daily work routine) after the fire alarm has sounded may decrease perceived risk level and cause someone to underestimate the critical nature of the situation [42,44,46]. Drawing on the authors' previous research [42], the model in this study calculates perceived risk levels by second using the equations given below:

$$P_i^{(t)} = P_i^{(t-1)} + \Delta P_{cue}^{(t)}$$
(1)

where $P_i^{(t)}$ is agent i's level of perceived risk at time period t, $P_i^{(t-1)}$ is i's level of perceived risk during previous time period t-1, and $\Delta P_{cue}^{(t)}$ is the change in perceived risk level at time t caused by observing emergency cues [42]. On the basis of agent i's current behavioral state, $\Delta P_{cue}^{(t)}$ is calculated as follows [42]:

$$\Delta P_{cue}^{(t)} = \begin{cases} \frac{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{I}^{(t)} - I_{N}^{(t)}}{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{I}^{(t)} + I_{N}^{(t)}}, \\ \frac{I_{EA}^{(t)} + I_{EW}^{(t)} - I_{N}^{(t)}}{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{I}^{(t)}}, \\ \frac{I_{EA}^{(t)} + I_{EW}^{(t)} - I_{N}^{(t)}}{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{N}^{(t)}}, \\ \frac{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{I}^{(t)} + I_{N}^{(t)}}{I_{EA}^{(t)} + I_{EW}^{(t)} - I_{N}^{(t)}}, \\ \frac{I_{EA}^{(t)} - I_{EW}^{(t)} - I_{N}^{(t)} + I_{N}^{(t)}}{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{N}^{(t)}}, \\ \frac{I_{EA}^{(t)} - I_{EW}^{(t)} - I_{N}^{(t)} + I_{N}^{(t)}}{I_{EA}^{(t)} + I_{EW}^{(t)} + I_{N}^{(t)}}, \end{cases}$$
(2)

where

- 1. if agent i's behavior is normal;
- 2. if agent i's behavior is investigating;
- 3. if agent i's behavior is evacuating at walking speed if agent i's behavior is evacuating at accelerated speed.

 $I_N^{(t)}$, $I_I^{(t)}$, $I_{EW}^{(t)}$, and $I_{EA}^{(t)}$ stand for the impact of other agents in a normal state ($I_N^{(t)}$), investigating state ($I_I^{(t)}$), state of evacuating at walking speed ($I_{EW}^{(t)}$), and state of evacuating at accelerated speed ($I_{EA}^{(t)}$), with these agents being observed by agent *I* at time *t* [42].

In the equations above, the impact of other agents in a different state (i.e., normal $(I_N^{(t)})$, investigating $(I_I^{(t)})$, evacuating at walking speed $(I_{EW}^{(t)})$, or evacuating at accelerated speed $(I_{EA}^{(t)})$), all of whom are observed by agent *I* at time *t*, is as follows [42]:

$$I_N^{(t)} = \sum_{j=1}^k \left| P_{Nj}^{(t)} - P_i^{(t-1)} \right|$$
(3)

$$I_{I}^{(t)} = \sum_{j=1}^{k} \left| P_{Ij}^{(t)} - P_{i}^{(t-1)} \right|$$
(4)

$$I_{EW}^{(t)} = \sum_{j=1}^{k} \left| P_{EWj}^{(t)} - P_i^{(t-1)} \right|$$
(5)

$$I_{EA}^{(t)} = \sum_{j=1}^{k} \left| P_{EAj}^{(t)} - P_i^{(t-1)} \right|$$
(6)

where $P_{Nj}^{(t)}$ is agent i's interpretation of the level of perceived risk surrounding agent *j* when agent *j* exhibits normal behavior between the values of 0 to 1, $P_{Ij}^{(t)}$ is agent i's interpretation of the level of perceived risk surrounding agent *j* when agent *j* exhibits investigating behavior between the values of 1 to 2, $P_{EWj}^{(t)}$ is agent i's interpretation of the level of perceived risk surrounding agent *j* when agent *j* exhibits evacuating at walking speed behavior between the values of 2 to 3, $P_{EAj}^{(t)}$ is agent i's interpretation of the level of perceived risk surrounding agent *j* when agent *j* exhibits evacuating at accelerated speed behavior between the values of 3 to 4, and $P_i^{(t-1)}$ is the level of perceived risk surrounding agent *I* at previous point in time *t*-1 [42].

On the other hand, perceiving and interpreting definite and credible signs of a fire (e.g., flame or smoke) triggers the most active response so that the individual in question will exit the danger zone as quickly as possible. In this scenario, perceived risk value is immediately elevated to the highest range of 3 to 4. If the level of perceived risk exceeds or is less than the threshold of its current behavioral state, an agent will make the decision to trigger a behavioral transition to the next active or passive

response stage [44]. The specific equations, model structure, and verification/validation processes for assessing the perceived risk of an individual agent can be found in Choi et al. 2018.

The second critical element, wayfinding ability, is likewise affected by an individual's cognitive capabilities. In order to follow an egress path out of a possibly dangerous environment, an agent should be able to correctly identify his or her current location in the building, assess alternative escape routes based on prior knowledge of the building layout, and make a decision as to the route and exit toward which he or she should move. Wayfinding ability would be restricted if the agent had a cognitive disability that impeded access to factors such as familiarity with the building layout and effective use of informative building signage (e.g., evacuation plans, exit signs). The model for this study accordingly includes the additional variables denoted in Table 4 to account for attributes of perception, interpretation, and decision-making which affect an agent's risk perception and wayfinding abilities. These attributes comprise certain innate characteristics hindering an agent's processes of perception, interpretation, and decision-making while establishing perceived risk and conducting wayfinding procedure. An agent with a value of 0.5 in perception ability, for instance, has only half the capacity to accurately perceive his or her surrounding agents and current location compared to an agent with a perception value of 1.0.

Agent Attribute	Value Range	Description		
Perception ability	0 to 1	Perceived risk	Ability to correctly perceive fire-related cues within a 20 meter radius from current position.	
		Wayfinding ability	Ability to correctly perceive location, path forward, and informative building signage within a 20 meter radius from current position.	
Interpretation ability	0 to 1 Perceived ris		Ability to correctly assess perceived risk based on observable fire-related cues.	
		Wayfinding ability	Ability to correctly use prior knowledge of the building and interpret perceived signage to find available routes and exits.	
Decision-making ability	0 to 1 Perceived risk		Ability to decide on the appropriate behavioral state based on level of perceived risk.	
		Wayfinding ability	Ability to decide to follow selected route option and egress building.	

Table 4.	Agent	attributes.
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As shown in Table 5, the last critical element, evacuation velocity, is determined by an agent's current behavioral state. The model presumes that an agent in a normal state will be stationary at a fixed position without any velocity. When investigating or evacuating at walking speed, the agent's velocity will be assigned the average walking speed of an adult moving inside a building, which amounts to a value between 0.6 to 0.8 m/s [55]. During the most active response to an emergency situation, the agent will run toward an exit at a velocity of 2.3 to 2.5 m/s [42,56]. However, as vulnerable building occupants are often unable to move as quickly as the emergency situation demands, the model sets evacuation velocity at a variable mobility range between 0 and 1. With full mobility, an agent will move at a walking speed of 0.8 m/s; velocity decreases to 0.4 m/s with a mobility value of 0.5.

On the basis of the survey results on the emergency response abilities, these values including perception, interpretation, decision-making, and mobility abilities are pre-assigned as an agent's fixed characteristics.

Response Level	Behavioral State	Velocity	
1	Normal	0 m/s	
2	Investigating	0.6 to 0.8 m/s [55]	
3	Evacuating at walking speed		
4	Evacuating at accelerated speed	2.3 to 2.5 m/s [56]	

Table 5. Behavioral states.

3.2.3. Simulation Settings

Simulations were conducted in an artificial environment (shown in Figure 4) which consisted of a single floor health care facility with six rooms, two main corridors, and three exits across a total area of 2400 m².



Figure 4. Simulation environment.

A total of 50 vulnerable occupants were dispersed at random inside the building alongside 20 healthcare providers. In order to represent different levels of movement, each simulation proceeded on the assumption that 30% of the occupants could move without support, 30% required additional support such as a wheelchair or crutches, and the remaining occupants would be able to move only if assisted by a member of staff. The size of each agent was represented as 0.45 m in width and 0.25 m in depth in accordance with the average shoulder width and depth of male adults [57].

4. Results and Discussions

Figure 5 illustrates the major causes for evacuation failure in a healthcare facility housing occupants with different disabilities. The survey respondents described groups of older adults (64.38%), groups with impaired hearing (80.64%), and groups with impaired cognition (75.00%) as those most likely to experience evacuation failure during a building fire because these occupants would remain unaware of the emergency situation. Several respondents indicated that older adults (6.8%), the mobility impaired (9.09%), and the cognitively impaired (4.16%) would not or could not attempt to evacuate the premises due to mobility- or cognition-related disabilities. Most of the responses concerning people with impaired vision (77.27%) and mobility impairment (71.42%) predicted that these vulnerable occupants would attempt to evacuate but likely fail to complete a successful evacuation due to difficulties in

finding available egress paths through which to vacate the building before conditions inside became unsustainable. According to the results of the survey, each vulnerable group experiences different factors that would have a significant effect on the outcome of their evacuation from a building fire.



Figure 5. Causes for evacuation failure in vulnerable groups.

Figure 6 summarizes the findings of the survey concerning the emergency response abilities of different vulnerable groups. Among the five vulnerable groups, the group of elderly citizens had the lowest ability index across all six criteria for cognitive ability and physical mobility. This group's ability to make evacuation decisions/select an egress route (M = 1.82) and perform a self-evacuation (M = 1.95) was significantly lower than in other groups. The impaired mobility group demonstrated opposite levels of capacity in terms of cognitive ability and physical mobility. Although they had the highest values for perception (M = 6.93), interpretation (M = 7.27), and decision-making (M = 6.45), the mobility impaired had relatively low self-evacuation (M = 3.09) abilities compared to other disabled groups. Even with assistance from staff, the group of mobility impaired occupants' ability to move along an egress path (M = 5.63) fell behind that of the remaining groups. Occupants with impaired vision were better equipped to perceive (M = 5.46) and interpret (M = 6.39) fire-related cues compared to occupants with impaired hearing (M = 4.32 for perception and M = 4.93 for interpretation), possibly because the most common indication of a fire is the sound of a fire alarm. However, visually impaired occupants were also less successful than other groups in both self-evacuation (M = 3.25) and evacuation with additional support (M = 4.53) due to constraints on seeing and selecting available exit routes. The group with impaired hearing reported the highest level of mobility. Finally, the survey responses showed that the group with cognitive impairment struggled with fairly low levels of ability during a fire evacuation, second only to the group of elderly citizens. Their capacity to make evacuation decisions or select evacuation routes was relatively lower (M = 1.91) than their other cognitive abilities (M = 3.00 for perception and M = 3.04 for interpretation). However, because of high mobility, their results for self-evacuation (M = 4.41), evacuation with additional support (M = 5.79), and evacuation with staff assistance (M = 7.08) was the second highest after the group with impaired hearing.



Figure 6. Survey results on evacuation abilities within vulnerable groups.

Table 6 uses these survey results to input each vulnerable group's values for perception, interpretation, decision-making ability, and mobility in comparison to a reference group without a disability (i.e., 1 for perception, interpretation, and decision-making ability, and a velocity of 0.6 to 0.8 m/s (walking) or 2.3 to 2.5 m/s (running) for mobility). The survey results were collected using a scale of 0 to 10, and each value was adjusted to a range of 0 to 1, as shown in Table 6, to be used as simulation input. Perception, interpretation, decision-making, and mobility variables were assigned as fixed values to represent response abilities of each group.

Table 6. Variables for perception, interpretation, decision-making ability and mobility.

	Perception	Interpretation	Decision-Making	Mobility
Reference Group	1	1	1	1 (velocity: 0.6 to 0.8 m/s (walking) and 2.3 to 2.5 m/s (running))
Older adults	0.245	0.234	0.182	0.195
Impaired mobility	0.693	0.727	0.645	0.309
Impaired vision	0.546	0.639	0.407	0.325
Impaired hearing	0.432	0.493	0.493	0.648
Impaired cognition	0.300	0.304	0.191	0.441

Figure 7 illustrates the evacuation performance and mean response/movement times of the five vulnerable groups and the reference group. Within 17.5 seconds, all building occupants in the reference group became aware of the emergency after the fire alarm sounded (t = 0); within 88.9 seconds,

the evacuees had egressed the building. Of the five vulnerable groups, the group that required the longest time to complete the evacuation process consisted of elderly citizens (263.3 seconds on average). It took M = 67.1 seconds for all agents to finalize their evacuation decisions and M = 196.2 seconds for them to clear the building. In terms of response time, the group of cognitively impaired occupants needed the longest time (M = 75.6 seconds) to make evacuation decisions, but their movement time was the shortest among all the vulnerable groups at an average of 138.3 s. The group with impaired mobility recorded the shortest response time (22.9 s) and the longest movement time (198.6 s). Between the vision and hearing impaired groups, agents with hearing impairment took slightly longer to finalize their evacuation decisions upon recognizing the emergency situation (M = 42.1 s) compared to the group with impaired occupants spent a longer period of time clearing the exits (M = 162.4 s) compared to the group with hearing impairment (M = 151.9 s), as the visual limitations of the former group made it difficult to identify available escape routes during evacuation.



■Response Time □Movement Time

Figure 7. Mean response and movement times of vulnerable groups.

The results of both survey and simulation confirmed that there were significant gaps in emergency response ability and evacuation performance among the five vulnerable groups. Each group's differences in cognitive ability and physical mobility affected their capacity for emergency response and successful evacuation during fire events. This suggests that vulnerable building occupants could evacuate a facility within much shorter timeframes if provided with special measures tailored to increase awareness of fire situations for cognitively impaired evacuees and the elderly. Although elderly evacuees also require assistance during the movement phase, the cognitively impaired would greatly benefit from assistive measures that increase their cognitive abilities (e.g., customized evacuation information devices) because they often have the strength to move faster than other vulnerable groups. Providing assistive mobile equipment to those with a limited range of independent movement could significantly improve their evacuation performance, considering that their response time was similar to that of the reference group and the shortest among all vulnerable groups. At the same time, the results of the study denote the need for special attention to be paid to the elderly for any meaningful reduction in their response and movement time. A singular general safety solution applicable to all vulnerable groups may not always be effective when ensuring fire safety for healthcare facilities. In this regard, the mixed approach of computer simulations and expert opinion can help us form a more in-depth understanding of the

various scenarios and obstacles that vulnerable evacuees face during unexpected fire situations, while simultaneously testing the effectiveness of modern fire safety technologies.

For example, Figure 8 summarizes how such an approach can be used to compare two different scenarios: (1) a normal condition evacuation involving vulnerable groups with healthcare providers, and (2) an improved condition evacuation involving vulnerable groups assisted by both healthcare providers and specialized evacuation equipment. In this simulation, every agent had already been trained to use specialized equipment, which could enhance their mobility up to a non-disabled person's average running speed (2.3 m/s to 2.5 m/s). Similarly, evacuation information devices provided customized information to each vulnerable group on the basis of the areas where they required assistance (e.g., vibrations and visual alerts for the hearing impaired), producing a 200% enhancement in their ability to perceive and interpret fire-related warning signals and find the shortest route to an exit. The use of evacuation equipment cut down on response time for the group with cognitive impairment by 38.49% (M = 46.5 s). The improvement in agents' perceptive and interpretative abilities led to an effective reduction in their response time. The use of assistive mobility equipment shortened both the impaired mobility group's evacuation time and response time. As the agents gained an enhanced range of movement inside the facility, they had more opportunities to perceive and interpret responses and behavior from other agents, prompting them to establish higher levels of perceived risk regarding the situation at hand and make faster evacuation decisions. Conversely, the impact of assistive evacuation equipment was the least effective when given to the elderly (M = -21.61%), perhaps due to the compounded nature of their restrictive conditions.

The effectiveness of assistive information and technology in reducing response time differed according to the evacuee's impairment. Movement time improved the most for the impaired mobility group using assistive evacuation equipment, marking a 31.52% reduction (M = 136.0 s). In this case, mobility equipment played a more important role in assisting a vulnerable occupant's egress than the evacuation information device. The use of the evacuation information device, in turn, may have been much more crucial in reducing movement time for the hearing and vision impaired groups, who needed 25.21% and 26.29% less time, respectively, to find the shortest route out of the building. The particular characteristics of emergency response ability and evacuation performance should therefore be considered in a more thorough and comprehensive manner, along with the impact that new measures will have when safety managers plan to apply new assistive information and technology to fire safety measures in a building. Also, the proposed method can be applied to analyze different scenarios such as facilities with a combination of different evacuee groups or higher population densities. Facilities with higher population densities, in particular, may demonstrate significantly different results from the present one due to stronger and more frequent interaction between agents, and such group dynamics may lead to both positive and negative impacts on evacuation performance. Therefore, various scenarios must be tested to apply the most appropriate designs and measures to secure evacuees' safety during an emergency. In addition, running the evacuation simulation in a 3D environment would provide a more insightful and easier understanding of evacuation characteristics of each vulnerable group when designing and planning assistive measures. An extended 3D model would be particularly helpful in visualizing vertical movement of evacuees, which is crucial for a successful evacuation of vulnerable groups, and how additional assistive measures can be helpful in enhancing their evacuation performance. Considering the fact that modern buildings are becoming more complex and higher, visualizations in 3D form will help safety managers and policymakers of facilities with vulnerable groups.





Figure 8. Comparison between normal and improved conditions.

5. Conclusions

This study examined different emergency response abilities and levels of evacuation performance in five groups vulnerable to high-risk situations during fire emergencies: the elderly, those with mobility impairment, those with vision impairment, those with hearing impairment, and those with cognitive disabilities. In order to gauge each group's ability to cognitively and physically respond to unexpected fire events, survey data was gathered from healthcare professionals employed at relevant facilities in South Korea. These data provided the input values for an agent-based evacuation model developed to test the response and movement time of the five vulnerable groups during a building fire. The results confirmed that each group's differences in perception, interpretation, decision-making, and movement corresponded to significant variance in evacuation performance. Cognitively impaired occupants displayed noticeable difficulties in making evacuation decisions due to their lacking an understanding of the situation around them. Despite understanding the emergency situation, the mobility and vision impaired groups experienced delays when moving along an egress path due to limitations in their physical capabilities. The group of elderly citizens demonstrated the most severe restrictions for both response and movement time to the point that they benefited less from assistive mobility equipment and customized information devices compared to other vulnerable groups. These findings emphasize the importance of incorporating a precise understanding of evacuation characteristics for vulnerable groups when designing and installing existing and new fire safety measures. Within such contexts, this study is expected to open new doors in analyzing disability-specific evacuation characteristics, as it uses survey data and a simulation model to test the feasibility of different evacuation scenarios when applied to various vulnerable groups whose emergency responses are difficult to observe in real-world situations.

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