GEOPHYSICS, VOL. 87, NO. 1 (JANUARY-FEBRUARY 2022); P. WA77–WA102, 5 FIGS., 1 TABLE.
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Evidence-based guidelines for protective actions and earthquake early warning systems

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ABSTRACT

Earthquake early warning (EEW) systems are becoming increasingly available or are in development throughout the world. As these systems develop, it is important to provide evidence-based recommendations for protective action so people know how to protect themselves when they receive an alert. However, many factors need to be considered when developing contextually relevant and appropriate recommendations. We have reviewed earthquake injury reports, protective action and communication theories, and behavioral research to determine what factors can guide inquiry and decision making when developing protective action guidelines. Factors that emerge from relevant literature include: (1) social, cultural, and environmental context, such as which people are present, what their social roles are, and in what type of building they are located when an earthquake happens, (2) demographic and experiential variables, such as gender and age as well as previous history with earthquakes; and (3) magnitude and intensity that influence the duration and impacts of the earthquake itself. Although we examine data from around the world, we focus largely on evidence-based recommendations for the U.S. system, ShakeAlert, because it provides a timely case study for understanding how people receive and respond to EEW messages. In addition to synthesizing relevant literature, we recommend pathways forward for this interdisciplinary research community that explores EEW and its application around the world. Consistency in collecting and reporting injury data globally may assist in aligning this fragmented literature to develop a richer understanding of how demographic, cultural, seismic, engineering, and technological issues can be addressed to reduce human suffering due to earthquakes.

INTRODUCTION

Earthquakes pose special risks to life safety because they are unpredictable, can occur in a sequence or series (e.g., a mainshock with hundreds to thousands of aftershocks, earthquake doublets, etc.), and are temporally and spatially variant events that can range in intensity (Mulargia and Geller, 2003). Even smaller magnitude earthquakes (M4.5+) can produce enough significant shaking such that damage can occur (Minson et al., 2021). This is especially true in places with poor land use planning and construction practices,

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weak building codes and standards, and otherwise aged or fragile building stock (Seaman et al., 1984; Alexander, 1985).

As a response, earthquake early warning (EEW) systems have been developed as a way to alert the public to pending ground shaking from an earthquake, to help protect infrastructure, save lives, and reduce the number of injuries. EEW entails the delivery of ground-shaking alerts or warnings to technical systems as well as to the public. EEW systems vary in their availability to different end users; some such as those in Mexico City, Japan, and the U.S.-based ShakeAlert system produce some public alerting (Figure 1). However, smaller scale systems deliver alerts to specific end users in Turkey, China, and Romania (Strauss and Allen, 2016; Figure 1). Other nations, such as New Zealand (Becker et al., 2020), are beginning to consider how they might use EEW systems. In 2006, the United Nations' International Strategy for Disaster Reduction created two critical documents that informed early warning systems: "Global survey of early warning systems" (United Nations International Strategy for Disaster Reduction, 2006a) and "Developing early warning systems: A checklist" (United Nations International Strategy for Disaster Reduction, 2006b). Both documents provide information about the development of early warning systems and how to develop these in the future. However, neither document outlined or explored protective actions — how to determine which are best for the warning system or how to include this critical information into the warning messages. Given the rise in interest regarding EEW, questions regarding which protective actions to include in messaging are becoming increasingly urgent to answer. A complete history of the development of EEW systems globally is available in Goltz and Roeloffs (2020).

In Figure 1, we illustrate the timeline of EEW following divisions noted by Allen and Melgar (2019). This timeline is supported in Reddy (2016) and Santos-Reyes (2020) for Mexico City and Mexico, Zollo et al. (2009) for Italy, and Nakayachi et al. (2019) for Japan. Alcik et al. (2009) describe Istanbul's EEW system development beginnings; India's system testing began in 2013 in the Northern Himalayas (Kumar et al., 2014; Mittal et al., 2019) and Romania in that same year (Allen and Melgar, 2019). South Korea's public alerting system started in 2015 (Sheen et al., 2017), Taiwan since 2016 (Xu et al., 2017; Chen et al., 2019; Wang et al., 2020), Sichuan, China, since 2018 (Peng et al., 2021), and in the USA via ShakeAlert in California since 2019 (McBride et al., 2020). Limited public alerting includes Israel (Nof and Kurzon, 2021) and Chile (Allen and Melgar, 2019). Google released its smartphone-based EEW system in New Zealand and Greece in May 2021 (Voosen, 2021; Figure 1b) and expanded it to Kazakhstan, Kyrgyz Republic, the Philippines, Tajikistan, Turkey, Turkmenistan, and Uzbekistan in June 2021; as of this writing, plans are underway to release a global EEW system by Google (Li, 2021).

For the purpose of this paper, we focus largely on evidence-based recommendations for the U.S. system, ShakeAlert, because it provides a timely case study for understanding how people receive and respond to EEW messages (see Figure 2 for a timeline of ShakeAlert development and significant earthquakes). Note that we do not suggest that the personal protective action of "drop, cover, and hold on" (DCHO) is the solution for all nations in all situations. Each nation can decide what protective action advice best suits their unique circumstances and context, taking into account cultural and social considerations. This need for context and education is vital in any humanitarian geoscientific project and especially so in the recently initiated ShakeAlert rollout given its reach to millions of people in California, Oregon, and Washington.

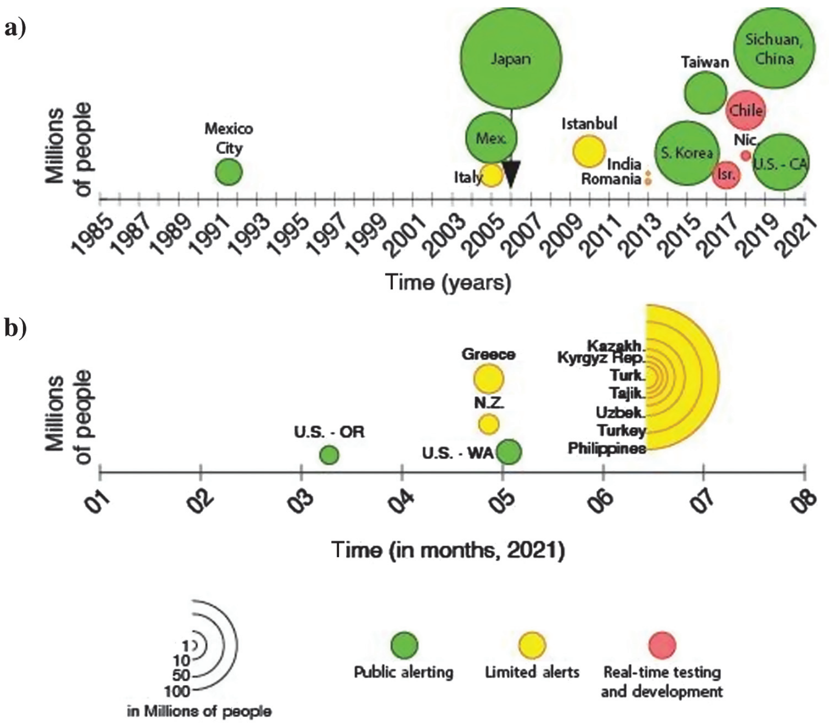

Figure 1. The timeline of EEW rollout around the world: (a) for 1985 through 2020 and (b) for 2021, scaled by the millions of people to be potentially notified with an alert. The colors represent the various stages of EEW rollout: public alerting (green), limited alerts delivered to technical users and/or pilot testers (yellow), and EEW testing and development (red), as defined in the legend. In 2017 and 2018, Israel (Isr.) and Nicaragua (Nic.) began real-time testing and development of their EEW systems, respectively. In (b), the limited public alerting (yellow) is delivered by Google Android only; thus, only people with an Android operating system phone can receive alerts.

THE DEVELOPMENT OF EEW SYSTEMS AND THE NEED FOR ASSESSING INJURY AND MORTALITY DATA FOR UNDERSTANDING HUMAN BEHAVIOR

The ShakeAlert EEW system in the United States is operated and managed by the U.S. Geological Survey (USGS), in partnership with the University of California at Berkeley, the California Institute of Technology, the University of Washington, the University of Oregon, and state emergency management agencies in the West Coast states. The ShakeAlert system has the capability to detect large offshore earthquakes, such as a Cascadia subduction zone event, but it will more likely issue ShakeAlert Messages for more frequent, smaller earthquakes with a minimum magnitude (M) of 4.5 or slightly larger (McBride et al., 2020; McGuire et al., 2021).

EEW systems such as ShakeAlert are designed to protect critical infrastructure and transportation systems and to promote public safety by offering people time to take protective actions (Minson et al., 2019; Santos-Reyes, 2019; Velazquez et al., 2020). EEW is made possible by a dense seismic network that detects and distributes alerts faster than the strongest shaking can arrive (Minson et al., 2019).

ShakeAlert technical partners started public alert delivery to wireless devices in California in 2019, with expansion to Oregon and Washington in 2021. Between October 2019 and January 2021, ShakeAlert messages were used by alert distribution partners to develop and deliver 30 alerts via smartphone apps and eight alerts via the Integrated Public Alert and Warning System (IPAWS) portal. Google delivers ShakeAlert-powered alerts as a service within the Android operating system. In addition, as of January 2021, alerts can be delivered via smartphone apps and the Android operating system (OS) at M4.5 or greater, whereas the IPAWS threshold is M5 to people who could feel a modified Mercalli intensity (MMI) of three, weak shaking, or greater (McBride et al., 2020).

The message content for ShakeAlert-powered wireless emergency alerts (WEAs) is "Earthquake Detected! Drop, Cover, Hold On. Protect Yourself. — USGS ShakeAlert," as illustrated in Figure 3. Using data in ShakeAlert messages, Google delivers alerts via the Android operating system using a bilevel alerting strategy. For earthquakes of M4.5 or larger, Google delivers a "Take action" alert to people who could feel MMI5+ (moderate shaking or greater) or a "Be aware" alert for those who could feel MMI3–4 (weak to light shaking).

Earthquake scientists have predominantly developed the concept and have been responsible for the technical implementation of ShakeAlert (Allen and Melgar, 2019). However, this effort is rooted in a vision to improve public safety and that means that EEW has strong social and humanitarian implications that warrant thorough social science integration (see Oreskes, 2015; Peek et al., 2020). Specifically, this means that developing a functioning system will require offering evidence-based protective action recommendations that will reduce injury and protect as many individuals as possible. The success of any technical system relies upon its appropriate use. In the context of EEW systems, this means that individuals and communities need to understand and be able to respond in the event of an alert (Reddy, 2016, 2020). This is especially important in earthquakes, when even the most advanced warning systems offer only seconds or perhaps minutes of lead time — this is in contrast

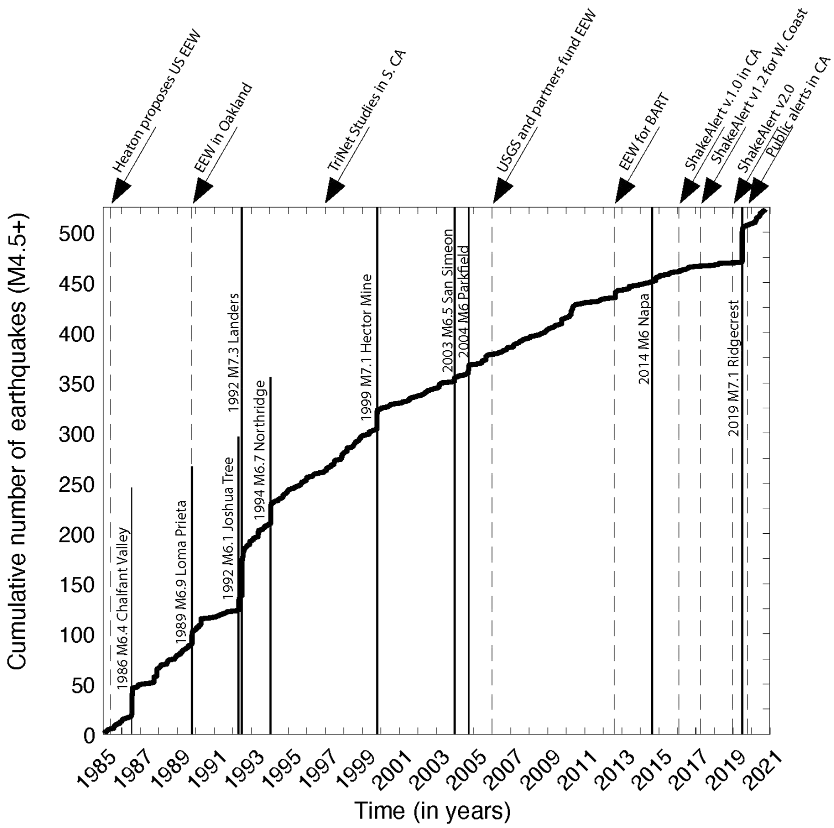

Figure 2. The timeline of the ShakeAlert rollout on the West Coast of the United States (the dotted vertical lines), over time from 1985 to 2021. These times are superimposed on the cumulative number of M4.5+ earthquakes for which the USGS issued a ShakeAlert Message in California, Oregon, and Washington (the thick black line) with notable M6+ earthquakes labeled (the solid vertical lines) over this same time period. Distribution partners develop and deliver ShakeAlert-powered alerts based on the data received in the ShakeAlert messages.

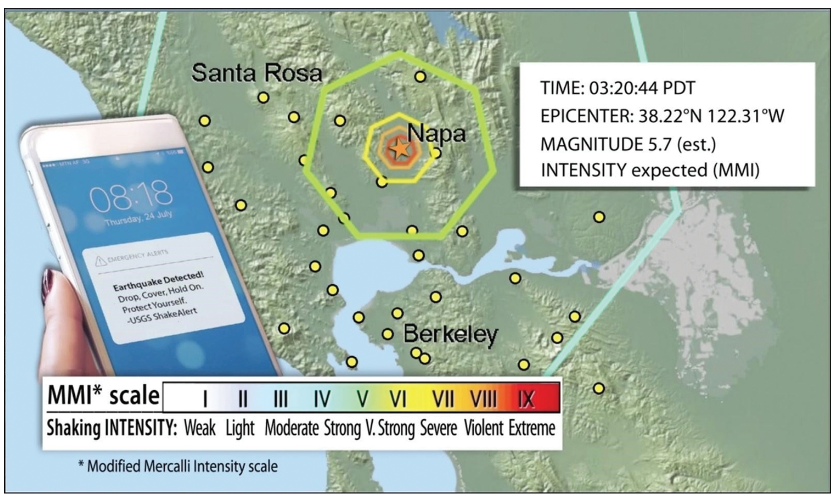

Figure 3. Image of a ShakeAlert-powered alert delivered via the IPAWS system, with the 2014 M6 Napa, California earthquake (with an orange star for its epicenter) and its MMI isoseismals with the scale in the legend. Seismometers that could detect the earthquake for the ShakeAlert system are shown as yellow circles. Image courtesy of the Incorporated Research Institutions for Seismology and adapted from the "What is ShakeAlert?" animation.

to hurricanes or tsunamis, for example, where advanced forecasting allows individuals days or hours to prepare (Goltz and Bourque, 2017; Michael et al., 2019).

For ShakeAlert specifically, only seconds of warning may be possible, given the physical limitations of the system combined with earthquake characteristics on the West Coast of the United States (McGuire et al., 2021). These limitations include how long it takes for messages to move through telecommunication systems, which are shaped by technological latencies and the detection processes that include algorithms and sensor networks (McGuire et al., 2021).

For EEW systems to be effective at protecting human life and promoting public safety, recommendations need to account for these technological limitations, variable seismic hazard and risk in a given geographic location, the quality and age of the built environment, and the knowledge and capacity of the population. Even in light of these complexities, the people receiving alerts need to understand and be able to perform the recommended protective actions during an earthquake. The recommendations for protective actions have evolved over time as infrastructure and technology have advanced, yet they still vary based on the geographic location, time of day, and social context. To create and refine evidence-based recommendations for the ShakeAlert system, relying on injury and mortality data from past earthquakes can provide important insight into human behavior during shaking. Other researchers have conducted similar studies, specifically the exemplar on landslide hazards, mortality, and recommended protective actions in Pollock and Wartman (2020).

EARTHQUAKE INJURY AND MORTALITY DATA: WHY DO PEOPLE GET HURT?

Global injury and mortality data are difficult to synthesize because earthquakes are so variable in intensity, location, and impact from year to year. In the past 20 years, 2000–2019, global yearly death estimates from earthquakes ranged from a low of 231 (in 2000) to a high of 298,101 (in 2004) (U.S. Geological Survey, 2021). Decades of earthquake research have found that oftentimes injuries are caused when individuals are moving to take protective actions, including evacuating from their location during an earthquake or immediately following an event (Goltz et al., 1992; Porter et al., 2006; Johnston et al., 2014; Horspool et al., 2020). Likewise, earthquake injuries may be exacerbated by nonstructural components of buildings. Crush injuries, for example, can occur when objects such as unsecured shelving, ceiling tiles, or even building floors fall onto people (Porter et al., 2006).

Although earthquake studies abound, especially following catastrophic events, comprehensive and comparable death and injury data are not widely available due to inconsistencies in data collection and reporting practices. Moreover, measuring disaster-related mortality and morbidity poses many challenges (Green et al., 2019) and most mortality studies only reflect officially reported deaths (for an exception, see Kano [2005], which relies on hospital admission data). De Ville de Goyet et al. (1976) evaluate the response to the 1976 M7.5 Guatemala earthquake and makes one of the first major attempts to compare earthquake fatalities globally and over time. Other attempts have followed major catastrophic earthquakes, including Peek-Asa et al. (2003) in response to the 1994 M6.7 Northridge earthquake. Tang et al. (2017) provide an updated literature review through a meta-analysis of 78 articles that explored earthquake injuries. We use data from all three of these articles, but we extend them further to include other data points. We searched Google Scholar using a variety of search terms, including "earthquake," "injuries," and "fatalities," and we limited our searches from 1970 to the present day, to reflect on modern building construction and standards. However, it is important to note that many older buildings may still exist in these earthquake areas and may not reflect newer building codes; these buildings vary in construction quality and potential for damage during shaking (Al-Nammari and Lindell, 2009). Other notable changes in our table are to use consistent moment magnitudes (M_W; Hanks and Kanamori, 1979; Duputel et al., 2012) and maximum ShakeMap intensities as reported by the USGS.

In Table 1, we present the magnitude, location, and maximum intensity for each earthquake as presented on the USGS event pages (United States Geological Survey). It includes more recent earthquakes and provides additional information about fatalities, injuries, and, where possible, demographic data such as gender and age. The table also includes other contributing factors, such as people moving during or immediately after the shaking. We further include whether there was an EEW system available and whether there was protective action advice provided if it was mentioned in the cited article.

Given the backdrop of injury and mortality data and growing EEW systems across the globe, it is important to understand why people behave the way they do during earthquakes. Key questions to consider include the following. Are people taking protective action? What protective action are people taking? How do they know what protective action to take? To answer these important questions, we turn to theories of human behavior to understand what influences decision making during an earthquake. By extending the work of Peek-Asa et al. (2003), Tang et al. (2017), and others, we can begin to further understand whether EEW reduces injury or fatalities, while accounting for numerous variables including magnitude, MMI, actions taken by injured people, cultural/social contexts, and whether there were protective actions campaigns prior to the earthquake.

USING THEORY TO UNDERSTAND HUMAN BEHAVIOR AND AS A PATHWAY TO SOLUTIONS: HOW CAN WE INTERPRET INJURY AND MORTALITY DATA THROUGH A SOCIAL LENS FOR PROTECTIVE ACTIONS?

Although protective actions are commonly depicted as an individual endeavor, the learning, understanding, and acting involved are inherently social. As Adams et al. (2017) write, individuals learn about disaster preparedness and response through observation, social modeling, and educational experiences that reinforce social norms, expectations, and attitudes. Moreover, effective risk communication is a key component in disaster preparedness and the appropriate learning of protective actions. For such risk communication to be successful, messages coming from trusted messengers through multiple channels that are clear, consistent, and easy to understand, and repeated often are best (Mileti and Fitzpatrick, 1991; Rowan, 1991; Sellnow et al., 2009; Maibach, 2019). Furthermore, research has found that the most effective warning messages consider the specific characteristics of the intended audience (Bier, 2001; Adams et al., 2017), offer specific instructions for protective actions, and provide actionable advice to mitigate risks (Mileti and Peek, 2000; Wood et al., 2012). If risks are presented without actionable advice

Table 1. Reported earthquake deaths and injuries and demographic and physical factors.

Earthquake date/magnitude/location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
29-02-1960 M5.8 Agadir, Morocco	IX	12,000 (estimated deaths)	Not available	Unknown — data source not confirmed	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
01-09-1962 M7.0 Buin Zahra, Iran	IX	10,000 (estimated deaths)	Not available	Cited from Lechat (1974)	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
31-08-1968 M7.1 Dashte Bayaz, Iran	IX	11,588 (estimated deaths)	Not available	Cited from Saidi (1963)	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
31-05-1970 M7.9 Ancash, Peru	VIII	66,784/143,331/ 20,000 missing	Rural communities were cut off from resources for longer periods of time in comparison to nonrural regions; this is due to road blockages (Caruso and Miller, 2014)	Census database, USAID Report (1970)	Unknown	Not reported	No	Spence and So (2009); table adapted from Spence (2007); Caruso and Miller (2014)
23-12-1972 M6.3 Managua, Nicaragua	VIII	6000 (estimated deaths)	Not available	Cited from Whittaker et al. (1974)	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
28-12-1974 M6.2 Hunza, Pakistan	VIII	5300 (estimated deaths)	Not available	Unknown — data source not confirmed	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
06-09-1975 M6.7 Lice, Turkey	VIII	3000 (estimated deaths)	Not available	Unknown — data source not confirmed	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
27-07-1976 M7.5 Tangshan, China 28-07-1976 M7.4 Hebei, China	X (XII)	242,769/79,900+	Provisional data (not the data source referenced in Peek-Asa et al., 2003).	Historical analysis; planning and recovery policy	Prior to these events, "China adopted the National Seismic Building Standards in 1959 and later strengthened the codes in 1974 and 1975" (Zhang et al., 2015)	Not reported	No	Peek-Asa et al. (2003), Zhang et al. (2015), and Rosenberg (2019)
04-02-1976 M7.5 Guatemala	IX	22,778/76,504	Children between the ages 5–9 and people >60 experienced higher mortality rates; Patzicia, Guatemala, had a 3.5% overall average death rate, children ages 5–9 had 5.6%, and people >60 had a 5.5% rate	Epidemiological studies; medical records	Prior to these earthquakes, there was minimal predisaster planning in place; immediately following the earthquake, the Ministry of Public Health and Social Welfare, the National Emergency Committee, and foreign assistance provided additional medical support	Not reported	No	Peek-Asa et al. (2003) and de Ville de Goyet et al. (1976)

Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/ location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
06-05-1976 M6.5 Friuli, Italy	IX	918 (estimated deaths)	Not available	Unknown — data source not confirmed	Unknown	Not reported	No	de Ville de Goyet et al. (1976)
23-11-1980 M6.9 Irpinia, Italy	IX	2700+ (estimated deaths)	Deaths 100× and injury rates >5× higher for trapped compared to nontrapped victims	Survey of 3619 people living in seven villages	Unknown	Promotes disaster relief efforts and community preparedness	No	De Bruycker et al. (1985) and Gizzi and Potenza (2020)
31-03-1983 M5.5 Popayan, Colombia	VIII	250–300 (estimated deaths)	41 pediatric injuries <15 years old (Jacquet et al., 2013)	Systematic review; databases and clinical records	Almost half of the fatalities reported in the Gueri and Alzate (1984) study result from "head injury"	No specific protective actions suggested, but this paper calls for "uniform age limits and injury classification systems"; Gueri and Alzate (1984) express the importance of comprehensive data collection and the creation of an epidemiological surveillance system	No	Jacquet et al. (2013) and Gueri and Alzate (1984)
19-09-1985 M8.0 Michoacan, Mexico	VII	9500/30,000	No gender differences reported; however, ages 15–64 comprised 70% of injuries in the Sanchez-Carrillo (1989) study	Medical records	"Awareness of danger, preexisting morbidity and immediate health status, location indoors or outdoors, time of day, and the activity engaged in at the initiation of a disaster — among other factors — probably play important roles in survival, in the extent of the lesions, and in the feasibility of searching for care. Morbidity and mortality rates could be decreased, as stressed in the literature, by enhancing preparedness and by including emergency safeguards in buildings in regions where natural disasters are common events" Sanchez-Carrillo (1989)	Yes, but only in certain states within Mexico	No	Peek-Asa et al. (2003) and Sanchez-Carrillo (1989)

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Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
07-12-1988 M6.9 Armenia	X	24,944/20,000 (from Spence and So, 2009); with Ministry of Health employees and their families — 831 deaths and 1454 injuries with $N = 32{,}743$ people	Geographic location, inside a building, height of the building, and location within the upper floors of a building were all risk factors for injury and death; the building height was most predictive of death more than location on floors or ground floor; death rates were fairly constant with age, except those in the 60+ group; females account for more deaths (496 out of 831); injury rates were higher for females than for males (Table 2 in Armenian et al., 1997)	Population-based study with a cohort approach of employees of the Ministry of Health and their families	"The best safety action to take is likely to depend on the specific type of building and may be different for densely populated urban areas versus rural areas" Armenian et al. (1997)	"Considering that most of the high-rise buildings destroyed in this earthquake were built using standard techniques, the most effective preventive effort for this disaster would have been appropriate structural approaches prior to the earthquake "Armenian et al. (1997);" It appears that the best safety actions to take in types of buildings similar to those in Armenia are to escape to the outside at the first instant of an earthquake or to seek safety in the first floors of a building" Armenian et al. (1997)	No	Peek-Asa et al. (2003) (total deaths); Armenian et al. (1997) (health care workers and their families)
18-10-1989 M7.1 Loma Prieta, California, USA	IX	63/3757	Building age, structure, personal protective actions, and sociodemographics are all risk factors (Jones et al., 1992)	Case-control study in the county of Santa Cruz ($N = 357$ for hospitalized/dead cases through proxy interviews)	3.32× greater risk in a building; "Many nonfatal injuries were associated with building occupants taking protective action. At least 60% of those injured during the period of shaking were engaged in some form of protective action at the time of their injury (Table 7). In total, 43% of this number was either attempting to evacuate a building, move to a safer place within a building, or, if already outside, move away from a structure. Typical evacuation injuries included tripping while running downstairs and jumping off loading docks while attempting to exit. One-quarter of those injured were either attempting to take shelter under a desk or table or were already underneath. In total, 14% was injured while standing in doorways or holding onto doors" (Peek-Asa et al., 2003)	Not reported	No	Peek-Asa et al. (2003); Jones et al. (1992); Pointer et al. (1992); Wagner and Krimgold (1994)

Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
20-06-1990 M7.4 Manjil, Iran	IX	45,000/60,000	Not reported	Unknown — data source not confirmed	Not reported	Not reported	No	Spence and So (2009); table adapted from Spence (2007)
16-07-1990 M7.7 Luzon, Philippines	IX	1621/3000	"The age of cases ranged from three months to 92 years (mean, 26 years), whereas that of the controls was two months to 81 years (mean, 26 years). The proportion of females was 55% for both cases and controls. Cases were more likely than controls to be single or widowed persons (odds ratio, 1.4) and were also three times more likely to have been transients (tourists or students) in the area when the earthquake struck"	An unmatched case — interviews	The behavior of individuals during this period was an important predictor of their survival. Escaping from a building during the earthquake was a protective behavior. At the start of the earthquake, 166 persons were on the ground floor of a building; cases were nearly three times as likely to have stayed inside (odds ratio, three; 95% confidence interval [CI], 1.3–6.6). Of the 361 persons who were outdoors at the start of the earthquake, those who remained there were less likely to have been injured than those who went inside (odds ratio, 0.3; 95% CI, 0.11–0.99). Only 18 (7%) of the 269 persons who remained inside a building during the tremor hid under a table or desk, a recommended evasive behavior to take during an earthquake. Of these 18 individuals, 12 were uninjured, whereas six sustained injuries such as contusions or minor abrasions. In schools, stampedes were caused by panic among the students and some teachers, and considerable numbers were injured as a result	Yes: only 18 (7%) of the 269 persons who remained inside a building during the tremor hid under a table or desk, a recommended evasive behavior to take during an earthquake	No	Tang et al. (2017) and Roces et al. (1992)
13-03-1992 M6.7 Erzincan, Turkey	VIII	498/2000	Not reported	Surveys, medical records; interviews with search and rescue workers, local and national residents	Unknown	Not reported	No	Angus et al. (1997)
29-09-1993 M6.2 Maharashtra, India	IX	9400+/30,000	Not reported	Unknown — data source not confirmed	Unknown	Not reported	No	Peek-Asa et al. (2003)

Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
17-01-1994 M6.7 Northridge, California, USA	IX	58 fatalities; 33 of these due to physical injuries; 171 fatal and hospital-admitted injuries examined	Age >65 to 2.9× greater risk of injury compared to younger persons; women 2.4× greater risk than men; compared to single-story structures, 3.8× more risk of injury in multiple-unit buildings and 2.9× risk to age and gender-matched controls; individuals in commercial buildings had 6× injury risk compared to both of those matched pairs	Population-based case-control study; case — fatal and hospital-admitted injuries; control — phone survey	Unknown	"Attempting to escape from buildings has been documented as a protective factor for death and a risk factor for death and injury. These are not necessarily contradictory, however, because exiting from a poorly built collapsing structure may protect against death, whereas attempts to exit buildings that do not collapse may increase risk for injury"	No	Peek-Asa et al. (2003)
15-02-1994 M6.9 Liwa, Indonesia	XII	207/2000	Not reported	Unknown — data source not confirmed	Unknown	Not reported	No	Peek-Asa et al. (2003)
16-01-1995 M6.9 Kobe, Japan	IX	6302/43,117 (Osaki and Minowa, 2001) 6432/40,092 (Japan Fire Defense Agency; in Spence and So, 2009)	People aged 50+ had increased mortality rates; gender did not increase the risk of injury; aged people slept on the first floors of wooden homes in this area and accounted for 45% of the deaths (Spence and So, 2009)	Descriptive and case-control studies, medical records	These studies also reported preventive factors, such as being on a road when the earthquake struck and running out of a building just after the first quake	One potential preventive factor found could be elderly people living on lower floors of buildings; this study mentions a series of potential actions such as fleeing buildings and staying in concrete structures	No	Peek-Asa et al. (2003) and Tanaka et al. (1999); Oskai and Minowa (2001)
17-08-1999 M7.6 Izmit, Turkey	IX	17,439/43,953 (Marza [2004] rebuts this number and puts the fatalities at 45,000, which contradicts the "official" numbers)	Not reported	Unknown	Not reported	Not reported	No	Spence and So (2009); table adapted from Spence (2007) and Marza (2004)
07-09-1999 M6.0 Athens, Greece	IX	143/2006	Median age: 38 years, although it spanned from 1.5–80 years old; 58 male and 53 female deaths; 108 people were Greek and three other nationalities; 50 at home, 57 at work, and four at other locations	Independent audit of data of 111 deaths (data were not available for the remaining 32 deaths)	Emergency management, training of emergency response forces, training in disaster medicine, and review of seismic protection policies are emphasized; "deaths may be reduced by improving the codes and surveillance on the construction of buildings"; fatalities mainly due to building collapse (89% of total)	Not reported	No	Spence and So (2009); table adapted from Spence (2007) and Papadopoulos et al. (2004)

Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
20-09-1999 M7.7 Chi-Chi, Taiwan	IX	2492/11,306/47 missing	1610 deaths (cases) in the study that were due to damaged dwellings; a slightly higher percentage of females compared to control group; 31.9% of deaths had ages >65 years; 45.3% of cases were farmers; "mortality risk increased with age for the adult population and increased with decreasing age for children younger than age 16 years"; the "results of this population-based cohort study suggest that health status and (socio-economic status) are two probable key predictors of earthquake death"	Taiwan government databases	Not reported	"The study results provide essential information to governments and the medical community on how to devise more efficient emergency evacuation procedures and how to better anticipate medical service needs after major earthquakes"	No	Chou et al. (2004)
26-01-2001 M7.7 Gujarat or Bhuj, India	IX	20,005/166,000	"56% (of casualties admitted in hospitals) were females, and 44% (were) male"; the average age of victims was 28; 541 deaths in Bhuj block — 171 children <14 years old (45.4%) and 107 women (28.4%)	Onsite interviews; victim-specific questionnaires were used at the Gandhi-Lincoln hospital Survey of 144 villages in Bhuj block except Bhuj city (Pawar et al., 2005)	This region lacked a central communication system and emergency medical services (e.g., ambulances services); all of the hospitals in Bhuj were destroyed causing 91% people to travel more than 200 km to find care, all "evacuation was carried out by the victims themselves" using family cars, trucks, and buses	Not reported	No	Roy et al. (2002); Vatsa (2002); Pawar et al. (2005)
28-02-2001 M6.8 Nisqually, Washington, U.S.	VII	1/400	"58 female (45.3%)/70 male (54.7) (reported in Kano, 2005)	Medical records	Falling was the most frequent cause of earthquake-related injury, as well as of nonearthquake related injury; other common mechanisms of earthquake-related injuries included overexertion, striking an object, and being struck by a falling object, which were not as common for nonearthquake related injuries; falls were more common among injuries presenting on the day of the earthquake, whereas proportionally more injuries resulting from overexertion presented on subsequent days. (Kano, 2005)	Not reported	No	Peek-Asa et al. (2003) and Kano (2005)

Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/ location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
03-02-2002 M6.5 Afyon, Turkey	VII	44/2000	Not available	Not reported	Not reported	Not reported	No	Tang et al. (2017)
26-12-2003 M6.6 Bam, Iran	IX	31,000/30,000	21 females (39.6%) and 32 males (60.4%) of study participants	Medical records	Not reported	Not reported	No	Ghodsi et al. (2006)
26-12-2004 M9.1 Sumatra, Indonesia	VIII	227,898 fatalities	This earthquake injury data are combined with the tsunami injury data; they are difficult to separate	Not reported	Not reported	Not reported	No	Spence and So (2009); table adapted from Spence (2007)
08-10-2005 M7.6 Kashmir, Pakistan (International Federation of Red Cross and Red Crescent Societies, 2006)	IX	69,000/86,000 (USGS impact summary); 70,000 +/200,000 (Spence and So, 2009)	Not reported	Red cross provided data	Not reported	Not reported	No	Rathore et al. (2008); Spence and So (2009)
26-05-2006 M6.3 Yogyakarta, Indonesia	VIII	6000/40,000/ 1.5M homeless	Not reported	1000 surveys totaling the representation of 4500 individuals	Not reported	Not reported	No	Spence and So (2009)
18-05-2007 M8.0 Peru	VIII	517/1090 (USGS impact report); 748/21,688 (Doocy et al., 2009)	Found “older adults and members of households of lower socioeconomic status” had a higher risk for injury; “no significant differences in injury risk between urban, periurban, or rural households”	Population-based cluster survey of households	“Crush injuries were the most common, accounting for 31% injuries, followed by fractures (23%), wounds (21%), and blunt force injuries (9%)”	“Study findings suggest that earthquake preparedness and mitigation efforts should focus on population subgroups of lower socioeconomic in rural and urban areas of earthquake-prone regions”	No	Doocy et al. (2009)
12-05-2008 M8.0 Wenchuan, China	IX	69,195/374,177	“Subjects older than age 75 and children between ages 10 and 14 were the largest population in their respective hospitals”	Cross section survey data	Following the earthquake, many hospitals were destroyed; access to medical care was significantly reduced	Not reported	No	He et al. (2011) and Zhang et al. (2009)
30-09-2009 M7.6 Padang, Indonesia	VIII	1117/12143515 injured according to Sudaryo et al. (2012)	“Physical injury is significantly correlated with higher disability and lower quality of life, whereas disability has a significant negative correlation with quality of life”; gender and age were not found to influence injury	Prospective cohort study	Not reported	Not reported	No	Sudaryo et al. (2012)

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Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
12-01-2010 M7.0 Haiti	IX	316,000/300,000 (USGS Impact summary); 222,750/300,000 (Doocy et al., 2009)	“Neither age nor sex was significantly associated with injury risk”; “Crowding had a significant impact on the rate of injury ($p = 0.014$), with households with between 2.0 and 2.9 individuals per room experienced significantly higher injury rates than those with fewer than 2.0 people per room”; “In the 40–49-year age group, the lowest mortality rate and highest injury rates were observed”	Cross-sectional cluster survey	Not reported	“Improvements in reporting, including standardization of methodologies and definitions and coordination between responding organizations may help to improve initial estimates of injury and mortality in emergencies”	No	Doocy et al. (2009)
13-04-2010 M6.9 Yushu, China	IX	2968/12,135/270 missing	In the orthopedic injury study on 582 patients, “adults accounted for 81.62%” of injuries, not significant among genders”; fractures, accounting for 60.94%” of all orthopedic injuries, with lower limbs being fractured the most; females were more likely to have pelvic and acetabular fractures, in comparison to males	Clinical data	Medical research focused greatly on physical injuries and outcomes rather than causes; thus, it is unclear what recommendations were already in place	Not available	No	Li et al. (2012)
03-09-2010 M7.0 Darfield, New Zealand	VIII	2815 injured	“A disproportionate number of females injured compared with males . . . most people injured were in the age range 40–59 years”; “1863 females versus 952 males (were injured)”	Analysis of the Researching the Health Impacts of Seismic Events (RHISE) database; population modeling using RiskScape multihazard impact modeling software	It was summarized that most injuries that happened during this event were the result of people moving in the dark while shaking occurred, as this earthquake happened earlier in the morning	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)

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Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/ location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
21-02-2011 M6.1 Christchurch, New Zealand	IX	181/1500 (9048 injured according to Basharati et al., 2020)	"A disproportionate number of females injured compared with males . . . most people injured were in the age range of 40–59 years"; "5960 females versus 3088 males (were injured)"; people between the ages of 40 and 49 had the highest rate of injury	Analysis of the RHISE database; population modeling	Many of the people injured in this event remained in one place while shaking occurred; "25% of both sexes tripped or fell during shaking and approximately 10% were hit by projectiles"	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)
11-03-2011 M9.1 Tohoku-Oki, Japan	VIII	15,854/26,992/ 3167 missing; Japanese National Police Agency — 15,854 dead/3167 missing/26,992 injured across 20 prefectures	"The mortality rate against the total population was 1.03%, whereas that of disabled persons was 2.06%"	Publicly available reports (i.e., government, media, and nongovernmental organizations)	Not reported	A need for more data on the number of fatalities and missing people; Fujii (2015) also recommends sustained and direct support of people with disabilities to mitigate damages (e.g., improved temporary housing conditions, transportation planning, and employment security)	Yes	Issue 31: Fujii (2015) (Internet); Japanese Society for Rehabilitation of Persons with Disabilities 2012; Zaré and Ghaychi Afrouz (2012); Japanese National Police Agency
13-06-2011 M5.9 Christchurch, New Zealand	VII	2057 injured	"1417 females versus 640 males (were injured)"; people between the ages of 40 and 49 had the highest rate of injury	Analysis of the RHISE database; population modeling using RiskScape multihazard impact modeling software	This study suggested that men are more likely to have taken protective action during shaking	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)
23-12-2011 M5.9 Christchurch, New Zealand	VII	1385 injured	"978 females versus 407 males (were injured)"; people between the ages of 50 and 59 had the highest rate of injury	Analysis of the RHISE database; population modeling using RiskScape Multihazard impact modeling software	This study suggested that men are more likely to have taken protective action during shaking	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)
20-04-2013 M6.6 Lushan, China	VIII	Not reported	Not reported	Not reported	Not reported	Not reported	No	Tang et al. (2017)
21-07-2013 M6.5 Cook Strait, New Zealand	VII	106 injured	Females were more than 2× more likely than males to be injured; "82 females versus 24 males (were injured)"; people between the ages of 40 and 59 had the highest rate of injury	Analysis of the RHISE database; population modeling using RiskScape multihazard impact modeling software	This study suggested that men are more likely to have taken protective action during shaking	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)

Table 1. Reported earthquake deaths and injuries and demographic and physical factors. (continued)

Earthquake date/magnitude/ location	Max MMI (USGS ShakeMap — ATLAS data)	No. of fatalities/injuries	Demographics of injury (female/male, age)	Data origination	Actions taken before/after earthquake	Protective action advice	EEW system present?	Publication
16-08-2013 M6.5 Grassmere, New Zealand	VII	166 injured	"112 females versus 54 males (were injured)"; people between the ages of 50 and 59 had the highest rate of injury	Analysis of the RHISE database; population modeling using RiskScape multihazard impact modeling software	This study suggested that men are more likely to have taken protective action during shaking	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)
20-01-2014 M6.1 Eketahuna, New Zealand	VII	49 injured	Females were more than twice as likely to be injured than males	Analysis of the RHISE database; population modeling using RiskScape multihazard impact modeling software	This study suggested that men are more likely to have taken protective action during shaking	Basharati et al. (2020) suggest education, refine self-protective actions awareness, and tailor campaigns to reduce rates of female injury	No	Basharati et al. (2020)
03-08-2014 M6.2 Ludian, China	VIII	615 fatalities, 3143 injuries	Not reported	Chinese government	Not reported	Not reported	No	Tang et al. (2017)
2015 M7.8 Kathmandu, Nepal, and aftershocks, to include 2015 M7.3 earthquake	IX (M7.3 had intensity of XIII)	8000/21,000	141 patients were studied in total — 117 spinal cord injury patients directly studied; female: male 1.3:1 (65 women in the study) — men are more commonly injured with spinal cord related injuries that are non-earthquake related; ages 2–86 years (mean of 36 years); 105 patients sustained injury during the M7.8, and seven sustained injury during the M7.3, with an additional five patients sustaining their injuries during other aftershocks	Medical records spanning 25/04/ 2015–16/06/2016	Not reported	"Certainly, improving the country's infrastructure with a focus on earthquake-resistant building codes is necessary for injury prevention; however, even simpler prevention campaigns such as the DCHO response to an earthquake may have adequately prevented some injuries"; two of these patients were wheelchair users who were unable to take cover or evacuate, highlighting the reality that disabled patients are at risk for further disabling injuries during a disaster; all patients with mobility impairments should be educated regarding disaster preparedness and adequate planning to maximize their own safety in the event of a disaster requiring evacuation	No	Groves et al. (2017)
2016 M7.8 Kaikoura/North Hurunui, Aotearoa/New Zealand	IX	2/620	68% (420) female and 32% male	Government-provided data	90% direct action from the person taking action during or immediately after shaking	DCHO suite of protective actions.	No	Horspool et al. (2020)

to reduce those risks, this can lead to fatalism and/or negative outcome expectancy (Becker et al., 2013; McBride, 2017), which reduces the likelihood of people taking action. Furthermore, explorations of cognitive theories and EEW systems are posited in Huggins et al. (2021).

Research has also shown that a technocratic model of one-way information sharing does not lead to action (Fischoff, 1995; Paton et al., 2005). Knowledge-deficit models that assume that people merely require more awareness and knowledge about a specific risk to take action have little evidence in their favor. Nonetheless, application of knowledge-deficit models is common in public education programs regarding earthquakes (Johnson et al., 2014; McBride, 2017). This strategy breaks down because, as social scientists and communications scholars have documented, information alone is unlikely to persuade people to change opinions, much less to take action. Instead, they are much more likely to be engaged when involved in what West et al. (2021) refer to as collaborative risk communication efforts, where risk communication products are coproduced by the people who are most at risk. In addition, as McBride (2017) notes, we are often more accepting of information that: (1) comes to us through channels we regard as reliable and trustworthy, (2) is designed to consider our specific needs, (3) fits with our mental models and world views, and (4) comes from a relatable and trusted source (see also McBride, 2018).

THEORIES REGARDING PROTECTIVE ACTIONS

Although hazards researchers use various theoretical lenses to explore and explain human behavior in the context of disaster, three that are especially relevant for understanding cognitive and social processes associated with earthquake-related actions include the protective action decision model (PADM), emergent norm theory (ENT), and mental models. These theories are especially helpful for considering why and when people take action (Neal and Phillips, 1988; Wood et al., 2018).

The PADM

PADM was developed for use in the context of natural hazards, including earthquakes. PADM focuses on how environmental and social cues are integrated with risk messages and other information in appraisal processes that inform decision making and protective behavior. PADM posits that protective action decision making begins with environmental and social cues and socially transmitted warning messages that then "initiate a series of predecisional processes that, in turn, elicit core perceptions of the environmental threat, alternative protective action, and relevant stakeholders" (Lindell and Perry, 2012). Although the model lays out progressive steps in the decision-making process, risk communication processes are dynamic and interactive (Lindell and Perry, 2012), which makes the specific context important to consider. PADM has been adapted and tested in a wide variety of hazard contexts (e.g., Nagele and Trainor, 2012; Terpstra and Lindell, 2013; Lazo et al., 2015; McCaffrey et al., 2018; Strahan and Watson, 2019), and it has proven to be a useful framework for identifying important contextual influences on protective action decision making and behavior. Although the PADM is a widely used social theory for protective actions, it continues to evolve through empirical testing of its predictive validity and application in different contexts (Lindell and Perry, 2012).

As evident from PADM, a common behavioral response is to seek additional information, or warning confirmation (Mileti and Sorensen, 1990; Wood et al., 2018). Earthquake alerts provide extremely short warning times (on the order of seconds), giving people no chance to seek warning confirmation. One of the challenges for organizations who manage EEW systems such as ShakeAlert is how to encourage or enable people to take protective actions, without requiring further confirmation either via social norming or information seeking.

ENT

ENT was originally developed in the 1950s, as explored in Turner and Killian (1957), but it has been updated further to explore human behaviors in unfamiliar and uncertain circumstances (Wood et al., 2018). Similarly to PADM, ENT begins with environmental and social cues. ENT posits that when a situation is uncertain or unknown, which is common when individuals get a warning message, they engage in activities to make sense of the situation before acting. This theory is particularly valuable because it emphasizes the social nature of human behavior and is concerned with how new norms develop in ambiguous situations among groups of people. For example, a key component of the theory is the notion of collective action, which focuses on how group behavior forms during moments of crisis or ambiguity (Arthur, 2013). One activity that individuals engage in during an ambiguous situation is milling, which is the social interaction that results in shared understanding of what is appropriate behavior in a given situation. ENT has been used in the study of WEAs (Wood et al., 2018) and offers an important theoretical foundation for understanding why individuals might respond in specific ways to alerts, particularly in group and social settings.

Mental models and trust in the system

As ENT highlights, social context, norms, and collective action are critical components of comprehension and appraisal of risk situations and new information. Mental models and associated prior experiences and expectations of the risk situation also influence decisions and actions, and they contribute to comprehension (Morgan et al., 2002; Bostrom, 2017). But when a person who lacks expertise faces an unfamiliar risk, or when uncertainty about a risk is high, trust is a key factor in communication effectiveness (Frewer and Salter, 2007; Science Communication Unit, 2014; Siegrist et al., 2021). Therefore, diminished trust can serve as a potential barrier to risk communication efforts, especially when public trust in the federal government is at historic lows (Pew Research Center, 2020) and science has become increasingly politicized among certain groups (Gauchat, 2012). Developing trust in a government-initiated, novel U.S.-based EEW system may present challenges for several reasons. First, the government agencies that are responsible for the development and issue of the protective action messaging are subject to broader forces of public mistrust (Pew Research Center, 2020). Second, the ShakeAlert states of Washington, Oregon, and California differ in political climate, earthquake experience, and the perceived safety of the building stock. False alerts may further challenge public trust in the newly established EEW system in the United States (McBride et al., 2020). As with any developing system, false alerts are inevitable as the system and technology advance. Of the 30 alerts issued by

ShakeAlert as of January 2021, two were false or inaccurate (McGuire et al., 2021), with the locations and distribution types illustrated in Figure 4.

Furthermore, based on people's proximity to the earthquake's epicenter, some end users received late alerts that arrived after ground shaking (McBride et al., 2020). There is not yet enough social science research to determine how these false or delayed alerts will shape public perceptions of EEW or the willingness to take recommended protective actions. However, prior research does indicate that there is some reason to be concerned about habituated inaction through the "cry wolf" effect. Such effects have been documented in controlled settings (as in Breznitz, 1984; LeClerc and Joslyn, 2015), but they are inconsistent in field settings (see Barnes et al., 2007). Case studies suggest that exposure to false alerts may have negative and positive effects on future protective actions, through encouraging some and discouraging others to take action (Tierney, 1993). In addition, as Reddy (2020) demonstrates through analysis of a false EEW alert in Mexico, concern over a potential cry wolf effect can lead to recriminations among alerting professionals rather than act as a facilitator for clear and responsible public communication related to enhancing system function.

PADM specifically explores receiver characteristics, but it does not explore further cultural contexts excluding social cues. Mental model research explores a wider range of factors that might drive risk-related behaviors, including more exploration of cultural and social contexts, similar to ENT. Wood et al. (2018) explore the use of ENT in relation to warning receipt and demographics such as gender, race/ethnicity, age, employment, income, and student status. Given that all three theories seek to further explain and contextualize people's actions in earthquakes and that demographics are a part of all three theories, the following sections explore the cultural and social contexts as well as demographics.

MAPPING EXISTING DATA TO THE WESTERN UNITED STATES: WHAT WE KNOW TO INFORM SHAKEALERT MESSAGING

People do not experience earthquakes out of context. These encounters are always embedded in lived experience and broader social and cultural systems. This means that what people know about earthquakes, where people are located, and whom they are with matter.

We found that the studies included in Table 1 do not use consistent data collection techniques or approaches, but they do indicate the importance of considering a range of factors when developing protective action recommendations for earthquakes. In an effort to categorize the broad factors that are present across these studies, we briefly describe three groups of variables related to protective action behaviors during and immediately following an earthquake. These include

1) social, cultural, and environmental context, such as who people are with, their social roles, and what type of building they are in when an earthquake happens
2) demographic variables, such as gender, age, and previous history with earthquakes
3) magnitude and intensity that influence the duration, impacts, and warnings of the earthquake itself.

These groups of variables are oftentimes linked and, when combined, account for a sizable proportion of the injuries experienced during earthquakes.

Social, cultural, and environmental context

Immediate social context — or one's proximity to others — during an earthquake can impact behavior (Lambie et al., 2017). Studies of earthquakes in Japan show that when dependent children were present during an earthquake, adults and children were more likely to take protective actions (Takuma, 1972; Archea and Kobayashi, 1984). Lambie et al. (2017) find that when dependent children were present during the 2011 Christchurch earthquake, adult individuals in the same area acted to protect the child using behaviors such as holding or carrying the child or helping the child in seeking shelter under a table or other sturdy object. The same study showed that people attempted to provide assistance to elderly individuals during and after an earthquake. Adding to the support for social context as a key variable in influencing behavior, Prati et al. (2012) find that people are more likely to flee a building during an earthquake if they are alone or with strangers away from home. Some researchers suggest that these variable results are shaped by how social roles and responsibilities of household members differ from roles and responsibilities in relation to the self or to strangers. If individuals are caretakers and responsible for others, those roles, professional capacities, and responsibilities persist during and immediately after an earthquake (Lambie et al., 2017).

Where individuals are during an earthquake also shapes what protective actions they take. For example, Goltz (2006) finds that if individuals are more familiar with an environment, such as being at home or work, they might be more likely to take the recommended protective action of DCHO. Vinnell et al. (2020) also find that people are more likely to respond to an earthquake by undertaking DCHO when inside a building in a potentially more familiar environment, as opposed to when outside. Conversely, if individuals are less

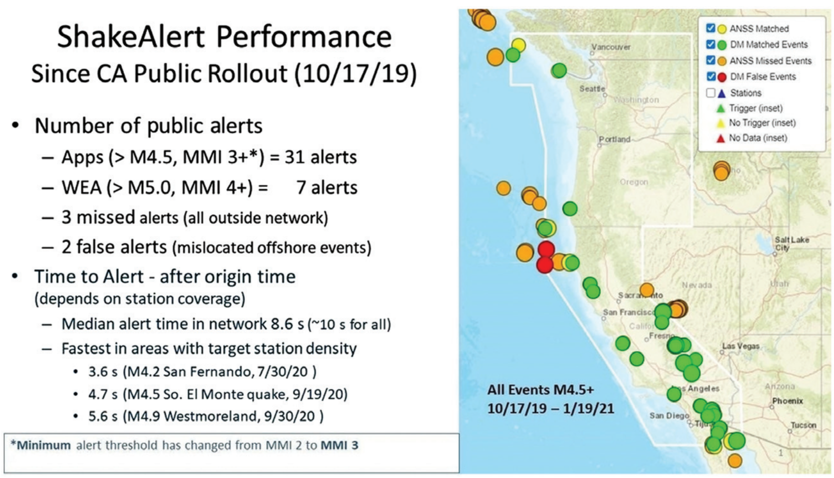

Figure 4. Number of public alerts since public alerting began in October 2019, with the locations, alerting channels, and timings of alerts.

familiar with their environment, they might be less likely to perform recommended protective actions (Goltz et al., 1992; Bourque et al., 1993; Lambie et al., 2017). However, in a recent study of earthquakes in eight countries, Goltz et al. (2020a) report that, contrary to earlier findings, location was not associated with specific protective actions undertaken.

Additional crucial contextual issues that inform whether and how people take protective action can include cultural traditions related to a seismic environment (see Aldrich, 2019). Such salient beliefs and traditions can, in turn, influence earthquake risk perception and preparedness actions (Mileti and Peek, 2002; Becker et al., 2013). Indeed, earthquake risk perceptions may differ tremendously between places and people, as cross-cultural studies demonstrate (Palm, 1998). Further, pioneering researchers documented what they call "disaster subculture" (Anderson, 1965; Wenger and Weller, 1973) in response to experiences with hazards. In particular, "seismic culture" is a way to describe how people live with earthquakes, often as a result of experience (Mileti and Darlington, 1997; Mileti et al., 2002; Parsizadeh et al., 2015). If the seismic culture is strong in a particular area, people's built environment is likely to reflect this concern with stricter building codes and better construction standards (Halvorson and Hamilton, 2007; Karababa and Guthrie, 2007; Ortega et al., 2017). Cultures can be understood as shared mythology, histories, stories, art, spiritual beliefs, politics, ordinary habits, and so on in ways that reflect and shape human behavior (García Acosta and Suarez-Rayunoso, 1996; Clancey, 2006; Valencius, 2013; García Acosta, 2017; Ibrion, 2017; Finn, 2018). Although, as Ibrion (2017) notes, many lessons from earthquake disasters of the past in her research site of Iran (as in many sites) have become "ignored and forgotten" only to be learned again when a new disaster occurs. Culture can be a resource for general seismic awareness and for educators who seek to build on that awareness and develop culturally relevant material suited to promoting protective action among specific groups.

Demographic variables

Research has also shown that demographic variables impact protective action decision making. In particular, certain demographic characteristics, such as gender, age, and past experience with earthquakes, can influence protective actions, frequently with mixed results (Lindell and Perry, 2000, 2004; Lindell and Whitney, 2000; Mallick et al., 2011; McBride et al., 2019; Horspool et al., 2020).

Studies have revealed gender differences in how people engage in earthquake protective action behaviors; however, some discrepancies have been noted in research findings. For example, research has shown conflicting results in regard to whether women or men are more likely to take protective actions (Bourque et al., 1993; Lindell and Prater, 2000). These discrepancies have been attributed to cultural differences and differences in earthquake features such as intensity and time of day. However, one consistent finding is that women are injured more often than men during the initial shaking and directly afterward (e.g., Peek-Asa et al., 1998; Taylan, 2015; Horspool et al., 2020). Gender scholars have argued that higher injuries among women can be attributed to women's role as primary caregivers, where they may rush to assist children or others for whom they are responsible (Horspool et al., 2020).

Age can also influence how people engage in earthquake protective actions. For example, studies on the behavior of children have found that older children were more mentally and physically prepared and able to perform protective actions during an earthquake compared to their younger counterparts (Alexander, 1990; Ramirez and Peek-Asa, 2005). Some of these differences were attributed to age and movement; as one study found, the younger the child, the more likely they were to move during an earthquake (Shoaf et al., 1998). Some scholars have asserted that as an individual ages, they gain a stronger sense of situational awareness and can better prepare mentally and physically for an event such as an earthquake (Ramirez and Peek-Asa, 2005; Prati et al., 2012). For instance, an analysis of individuals' immediate earthquake behavior response in New Zealand and Japan found that, in both countries, older people (those 65 and older in age) were "more likely to continue normal activities or protect property and were less likely to take cover or to protect persons" (Lindell et al., 2016). Glass et al. (1977) study injury data in the 1976 M7.5 Guatemala earthquake, linking age and cosleeping behaviors, with younger children more likely to die compared to their older siblings when sleeping together rather than with their mothers.

Studies on risk perception, perceived hazard knowledge, and protective measures found that respondents who lived in a known risk or hazard area were more likely to take protective measures compared to those not living in close proximity to a risk or hazard (Lindell and Whitney, 2000). Some scholars found that past experience is a motivating factor in using protective actions, whereas others found that past experience causes a form of risk mitigation complacency (Lindell and Perry, 2004). For example, one study reported that those with past earthquake experience often have a false sense of earthquake security that may lead to little or no protective action motivation (Lindell and Perry, 2004). An EEW study from Japan also highlighted that participants were unlikely to take protective action on receipt of an earthquake warning, potentially due to optimism based on previous experiences in which strong shaking had not ensued (Nakayachi et al., 2019).

Earthquake characteristics

Given the many variables that influence earthquake outcomes, the magnitude of an earthquake alone is a poor measure of its human impact. Rather, we should focus on an earthquake's intensity, which depends on the magnitude, depth to the hypocenter, distance from the rupture, the soil and rock conditions, and the directivity. The original MMI scale by Wood and Neumann (1931) was a 12-point scale based on qualitative factors. These factors included descriptions of what people may experience at these different levels and what damage they may face, such as cracks in the walls at lower intensities or bridges collapsing at higher intensities. The descriptions made by Wood and Neumann (1931) predate a measure of instrumental intensity, which typically can be determined from peak ground acceleration (PGA) measurements recorded at spatially distributed seismic stations. However, seismic stations in any given region may be sparse. Today, intensity is based on a 10-point scale (e.g., Stover and Coffman, 1993) and is determined through seismic records, damage reconnaissance, and/or through "Did you feel it?" reports (e.g., Wald et al., 1999, 2011; Dewey et al., 2000).

Earthquake intensity scales have historically used three criteria for intensities: impacts on buildings and infrastructure, geologic and environmental changes, and human behavioral response (Goltz et al., 2020a). Stover and Coffman (1993) conclude that the human behavior criteria at higher intensities were unreliable due to a lack of empirically grounded social scientific work. Thus, the USGS removed references to human behavioral response at intensities IV through VIII, likely because behavioral response to shaking is so diverse that it cannot be included on a scale that is intended for global use (Goltz et al., 2020a). USGS information products such as prompt assessment of global earthquakes for response (PAGER) and ShakeMap (e.g., Worden et al., 2010) use MMI, and, in the case of PAGER, infrastructure and population information for rapid response is also used (Thompson et al., 2020).

Although earthquake intensity varies from place to place, many studies suggest that, during an earthquake, people pause for a moment when they first experience shaking (Lambie et al., 2017; Zhou et al., 2018; Bernardini et al., 2019; Goltz et al., 2020b), which has also been seen in an earthquake warning context (Nakayachi et al., 2019). As stated previously, rather than immediately taking action, people may also engage in milling behavior, where they seek out information or others to confirm their earthquake experience (Wood et al., 2018). Goltz et al. (2020a) note that the amount of time someone will need to assess the situation before acting relates to shaking intensity; however, this may be less relevant in the context of EEW, when people would receive messages before strong shaking arrives, except for those in the late-alert zone. Specifically, studies have documented that the more intense the shaking is, the less time people will wait to act (Zhou et al., 2018; Bernardini et al., 2019).

What is clear throughout the literature is that human behavior during and after earthquakes is complex and context dependent. The growing body of social science literature can provide important insights into actions that people take during and after shaking and how those potentially relate to injuries. Therefore, we need to take into account contextually relevant recommendations, campaigns, and education, to include the cultural appropriateness of certain actions.

HOW CAN EEW SYSTEMS AND THE ASSOCIATED CAMPAIGNS BUILD FROM THEORY AND DATA TO PROVIDE EVIDENCE-BASED RECOMMENDATIONS?

In this paper, we are especially concerned with the connection between preparedness information and protective actions. Given this, our focus now shifts to the messages diverse people receive *before* an earthquake about what they can do *during* an earthquake. We recognize that many people move in and out of various spaces throughout the day — home, work, school, parks, playgrounds, cars, public transportation, and so forth. However, according to the Environmental Protection Agency, approximately 93% of Americans' time is spent indoors (U.S. Environmental Protection Agency, 1987). For that reason, we further narrow our emphasis to protective action messaging for people who are inside buildings.

Research suggests that people are at risk for injury caused by building collapse or impacts from nonstructural debris (Petal, 2004; Ashkenazi, 2008; Johnston et al., 2014). In the United States, many buildings are built of wood, composite, or other light materials, whereas in other countries, such as Israel, buildings are more commonly made of concrete and other heavier materials that might cause more severe injuries or fatalities in the event of a building collapse (Rapaport and Ashkenazi, 2019). When a building does not collapse and is designed to withstand ground shaking, people inside are primarily at risk of being injured by unsecured furniture and other falling objects (Goltz et al., 2020b). However, when a building is not designed to withstand ground shaking, the people inside are primarily at risk of being injured by partial or total building failure. For developing nations, Goltz et al. (2020a) find that flight from buildings during an earthquake was highly salient and that for residents in these countries fleeing outside a building may seem to be a better option than being trapped by debris from a collapsed building. As they note:

> In choosing one response strategy over another, perceptions of vulnerability may be as important as education and drills. Essentially, response in an earthquake should be considered highly contextual and interpretations of success will depend more on ultimate survival and avoidance of injury than any universally accepted pre-earthquake strategy (Goltz et al., 2020a).

Protective action campaigns attempt to educate and train individuals about what specific actions to take during an emergency (McBride et al., 2019) through efforts such as drills (Adams et al., 2017; Santos-Reyes, 2020; Vinnell et al., 2020), K-12 educational programs (Tipler et al., 2017), and public message campaigns (McBride et al., 2019). Protective actions for earthquakes are explored in detail in Wood et al. (2018) and the Geohazards International (2021). Both documents explore the kinds of protective actions in various nations including DCHO, evacuation/flee, stay indoors, take cover under doorways, and move to a "safe area" (Wood, 2018; Wood et al., 2018). For this paper, we explore the main protective actions suggested for EEW when inside a structure: (1) seek shelter under an object, most commonly known as DCHO and (2) evacuate the building to an outside area or a safer location in the building (Shapira et al., 2018). It is worth noting that these and other recommendations have evolved over time based on studies of human behavior during earthquakes, and much of this information comes from studies of populations in developed nations using survey data (Goltz et al., 2020b).

The evolution of recommendations has gone in both directions, from evacuation to DCHO and vice versa. For example, McBride et al. (2019) explore how over the course of several decades, protective action recommendations in New Zealand evolved from evacuating; to seeking shelter under tables, desks, and doorways; to drop, cover, and hold. In contrast, Rapaport and Ashkenazi (2019) detail how a national expert committee in Israel recommended changing protective actions in schools from DCHO to evacuate to an open space. Understanding the reasons for these changing recommendations and why certain protective actions are recommended in different locations is critical for future emergency managers, scientists, educators, and public officials who are charged with promoting protective behaviors in a range of geographic and cultural contexts with varying levels of earthquake risk. In the subsequent sections, we focus on the two global primary recommended protective actions, which are DCHO and flee outside or evacuate to a safer space.

Recommendations for DCHO and the associated campaigns

DCHO is the current recommendation in the United States, Japan, and New Zealand (Rapaport and Ashkenazi, 2019). These nations are characterized by advanced levels of development, and most recently constructed buildings are resistant to earthquake ground motion (Goltz et al., 2020a). According to McBride et al. (2019), coordinated protective action campaigns in the United States that resemble the current DCHO began with "Duck and cover" in 1951. This campaign, which was developed largely in anticipation of a nuclear blast, involved teaching school children how to duck under their desks and cover. In the 1960s, protective action campaigns refocused, particularly in schools, to warn of fires and ultimately gave rise to modern fire drills (Johnston et al., 2013). Protective action campaigns for earthquakes varied over time after the 1960s, with schools teaching duck, cover, and hold before the message was refined to DCHO (Jones and Benthien, 2011). Today, more than 50 nations participate in the annual great ShakeOut, which is the largest earthquake drill globally that encourages participants to practice DCHO and other earthquake preparedness actions during a designated day each year.

DCHO represents a suite of protective actions that goes beyond dropping under an object, such as a desk or table. These other protective actions include what to do in different environments (e.g., in bed, outside, and in a moving vehicle) and for differently abled persons such as those requiring a cane, walker, or wheelchair. This is important to consider when thinking about how to relay messages to the public and prepare people to take action during an earthquake. Indeed, as McBride et al. (2019) note, fully performing the entire DCHO might not be completely achievable "depending on the PGA and the shaking intensity felt during an earthquake." During particularly intense earthquake shaking, MMI 7 and above, people might not be able to walk to actually get under an object, and being close to an object might allow for greater ability to perform the recommended action (Lambie et al., 2017). Recognition of this variability has prompted changes to recommendations to emphasize the need to drop wherever an individual is, in an effort to avoid injury to the head or neck and injury from tripping and falling (Johnston et al., 2014). Given this, Johnston et al. (2014) argue that the most important part of the DCHO action is "drop" because this stops people from taking further action, like moving, which can cause more injury (Horspool et al., 2020).

Although ShakeAlert-powered alerts could provide seconds of notice that shaking is imminent (Minson et al., 2019), it may not supply enough time for people to safely evacuate, leaving them in a vulnerable position attempting to flee a building with falling debris, as occurred in the 2001 Nisqually, Washington, earthquake (Kano, 2005) and in the 1933 Long Beach, California, earthquake (Trifunac, 2003).

Recommendations to flee outside or evacuate to a safer space

In countries such as Israel and Mexico, as well as developing nations such as Haiti, Nepal, and Pakistan, the current recommendation for people in smaller buildings or those on lower floors is to flee outside to an open space (Rapaport and Ashkenazi, 2019; Goltz et al., 2020a). In the case of Mexico, people in tall buildings are recommended to DCHO; thus, their public education campaigns are situational rather than universal. As noted previously, Israel recently changed its recommendations for all school buildings, indicating that if children are in the building during an earthquake, they are advised to flee outside rather than drop and cover (Rapaport and Ashkenazi, 2019).

In these and other associated instances, evacuation implies moving from one area to another. But as Goltz et al. (2020b) emphasize, the recommendation does not have to mean moving from indoors to outdoors; it can imply movement to a place of increased safety. In a scenario in which evacuation is the recommended action but fleeing outside would take more than a few seconds, the preferred protective action is to flee to a safer space within the building (Goltz et al., 2020a), as determined by structural engineers (Rapaport and Ashkenazi, 2019). For example, if school children were inside of a gymnasium during an earthquake, where there was a high chance of falling debris, they may be encouraged to move to nearby classrooms or to a cafeteria, where there may be tables or other objects for the children to use as cover.

As indicated by the aforementioned example, the type of furniture in a specific building can shape the recommended protective actions concerning evacuation versus sheltering. Essentially, we ask, would the furniture be large enough to cover all individuals, and would it be strong enough to protect individuals in the event of a strong earthquake? For kindergartens in Israel, in particular, the expert committee recommended fleeing to a safer space because many tables built for children are made from lightweight materials and they would not actually be able to protect them, even if they were able to DCHO. Moreover, the report found that the tables were not actually large enough for all of the children to fit under (Rapaport and Ashkenazi, 2019). At this time, we could find no evidence in the literature of a standard flee out protective action campaign that would be equivalent to that of ShakeOut.

As Goltz et al. (2020a) observe, it is difficult to identify when a significant share of the building stock is safe enough that recommendations to flee outside should be replaced by DCHO and how cultural beliefs might not advance at the same rate as building improvements. For example, Mexico and China have advanced rapidly in terms of building codes and economic growth, yet beliefs about protective actions were not always consistent with the capacity of buildings to resist earthquakes (Goltz et al., 2020a). In short, beliefs that fleeing to the outside may prevail despite strengthened building codes. Thus, recommendations in these areas need to be guided by structural engineers, emergency managers and planners, seismologists, social scientists, and local leaders. No single action is recommended or appropriate on a global scale (GeoHazards International, 2018; Goltz et al., 2020a).

Recommended actions for persons with differing abilities and needs

One key area that is underexplored in the social science literature on protective actions is how recommendations, whether it be to DCHO or evacuate, do not always account for differing abilities to perform the action. McBride et al.'s (2019) study underscored the need for addressing ability and fragility in protective action recommendations and how certain groups, such as pregnant persons, persons with a disability, medically compromised individuals, or individuals with a high body mass index, may struggle to complete DCHO more than others. This work emphasized that members of these groups may find it difficult or impossible to fit under a table comfortably or safely (McBride et al., 2019).

Although some emergency management agencies and risk communication experts have started to incorporate tailored messaging into protective actions campaigns, there are many underserved populations who have little to no representation in this work. One potential example of inclusivity is the ShakeAlert campaign, where messages were adapted from the ShakeOut campaign to feature individuals who use a cane, walker, and wheelchair, and describe how each can perform DCHO recommendations (see Figure 5a).

ShakeAlert's communication materials are also available in multiple languages, including English, Spanish, Vietnamese, Chinese

(Mandarin), Tagalog, and Russian. Although these are important inroads for access and understanding, much more work needs to be done to approach protective action recommendations from a diversity, equity, and inclusionary standpoint that accounts for systemic issues that affect an individual or community's level of social vulnerability (Jenkins et al., 2021). We now explore the evidence-based recommendations for ShakeAlert.

EVIDENCE-BASED RECOMMENDATIONS FOR SHAKEALERT AND THE WESTERN UNITED STATES

Considerations for public safety and ShakeAlert began in 1997 with the TriNet studies, explored in Goltz (2003) and Hauksson et al. (2001), suggesting that further research would be required regarding the public-facing components of the system. As the system evolved, as illustrated in Figure 2, it became apparent that for the ShakeAlert System, many people may have only a few seconds notice to take action in most cases (McGuire et al., 2021). Because the amount of warning time is a critical component in determining what protective actions are feasible (Minson et al., 2018; Wald, 2020), many people will receive only seconds of warning on the West Coast of the United States. We examined research articles that included information on how people were injured and what actions they took, as well as nations with a variety of built environments. Close examination of injury data of relevant earthquakes experienced in California, from the 1989 M6.9 Loma Prieta and 1994 M6.7 Northridge earthquakes (Shoaf et al., 1998), found that people were twice as likely to be injured when moving during shaking. Kano (2005) finds that a large portion of injuries occurred while people were exiting or moving away from buildings, with bricks and other material falling on them as they fled. Furthermore, schools in the Philippines were evacuated during shaking; this process caused trampling injuries (Roces et al., 1992). From the Peek-Asa et al. (2003) article, they found that: "attempting to escape from buildings has been documented as both a protective factor for death and a risk factor for death and injury. These are not necessarily contradictory, however, because exiting from a poorly built collapsing structure may protect against death, while attempts to exit buildings that do not collapse may increase risk for injury." Basharati et al. (2020) find that 25% of people injured tripped or fell during shaking. This finding is consistent with other studies, including Horspool et al. (2020) that again find that moving while shaking can increase the risk of injury. We found one article, from an earthquake in Armenia, that suggested that the only means of survival in that earthquake was evacuation from buildings (e.g., Armenian et al., 1997). Most of the studies in states where ShakeAlert will be active or countries with similar built environments suggest that the main source of injury is moving during shaking. This finding, combined with short alerting time frames (10 s or fewer), indicates that people are unlikely to be fully evacuated from buildings before strong earthquake shaking occurs. Thus, we suggest that DCHO is the best course of personal protective action to recommend for the alerts.

Further, DCHO action is already part of an active earthquake drill, ShakeOut, that reaches tens of millions of people in the United States and abroad each year. This suggests that when children as well as adults receive a ShakeAlert-powered alert, it tells them to take the protective actions that they would normally take when they feel earthquake shaking, only with more warning time. This means that when people receive an alert, they may have already built procedural knowledge of what actions to take (McBride et al., 2019). Thus, the alert serves to activate preestablished action plans. Although ShakeOut is not a panacea and researchers continue to learn how effective the drill is (Goltz et al., 2020b), it is an established campaign with significant reach. Improvements to alert content that is delivered in the future could include images, such as the DCHO icons, as explored in Sutton et al. (2020), as well as the ability to present warnings in more languages and other means to broaden accessibility (McBride et al., 2020). Research currently suggests that people are more likely to stop and stay put (i.e., freeze) or, in the United States, to stand in a doorway, than they are to DCHO in an earthquake (Dunn et al., 2016; Goltz et al., 2020b), which suggests that outdated advice and insufficient practice or experience may be among the barriers to DCHO. One important barrier for people performing DCHO is embarrassment; more frequent drilling or use of humor may reduce this emotion over time (McBride et al., 2019).

In the context of the United States, messaging for specific demographic groups, combined with site-specific training, could greatly increase the efficacy of ShakeAlert-powered alerts, which include the DCHO message. Dunn et al. (2016) and Goltz et al. (2020b) suggest that people are more likely to freeze or stop where they are than DCHO. The ShakeOut campaign has had some success in assisting people in knowing what protective action to take for earthquakes; however, further campaigns beyond an annual earthquake drill may be needed specific to ShakeAlert. ShakeAlert could consider its own tests, drills,

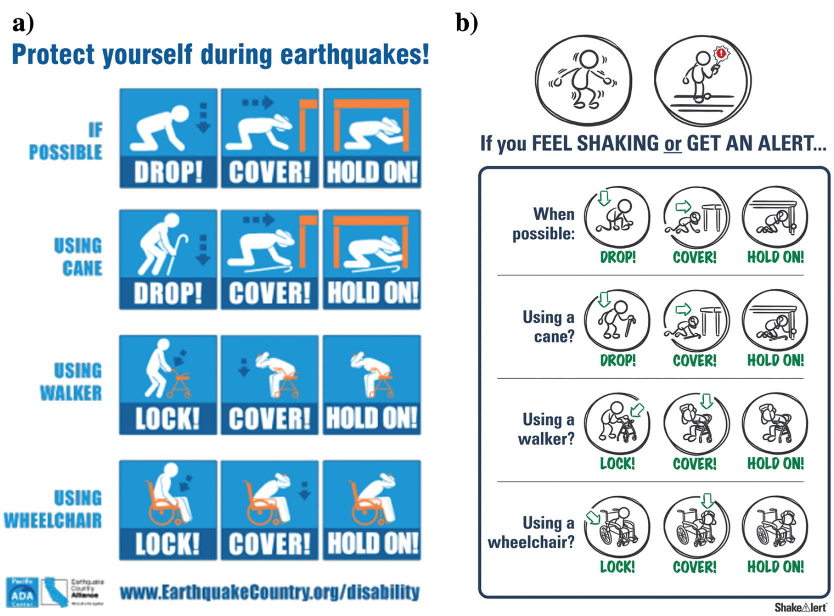

Figure 5. (a) The original figure from the ShakeOut campaign. (b) The redesigned image for ShakeAlert, which is meant to reach a more diverse segment of the population with a range of abilities to take recommended protective actions.

and other engagement opportunities to extend and fortify people's knowledge of the correct protective actions to take.

FUTURE DIRECTIONS FOR PROTECTIVE ACTION RESEARCH

In this paper, we have demonstrated that creating protective action recommendations for earthquakes is a complex task that requires consideration of a variety of situational, contextual, and sociodemographic factors. The variables that influence protective action decision making are critical for social and natural scientists, engineers, public officials, emergency managers, and myriad other social actors to understand when recommending risk-reduction strategies. We argue that an approach that is firmly grounded in the best available social science evidence will allow for a better understanding of human behavior in relation to earthquakes and more successful risk communication efforts. In addition, we outline why there is no universal standard for recommended protective action at this time and therefore encourage disciplinary experts and emergency managers to work together to comprehensively develop recommendations that are contextually appropriate given the earthquake risk, technology available, status of the built environment, and other social, cultural, and demographic considerations that may encourage or hinder people from taking action.

One recommendation is that when the United Nations updates its two key documents — "Developing early warning systems: A checklist" and "Global survey of early warning systems" — they could consider protective actions and how to determine what protective actions are best depending on the hazard and warning system, which may increase the efficacy of these types of systems. This could include adding how to analyze or collect injury data from the hazard in different nations, understanding earthquake characteristics to determine best- and worst-case scenarios for warning times, and deciding what protective action is most culturally and socially appropriate. We realize that DCHO may not be the best protective action for all places; however, we do suggest that some analytical processes inform the decision-making process for choosing which protective actions to recommend for EEW. In this paper, we explored three key considerations that can guide inquiry and decision making when developing protective action guidelines:

1) social, cultural, and environmental context, such as which people are present, what their social roles are, and in what type of building they are located when an earthquake happens
2) demographic variables such as gender, age, and previous history with earthquakes
3) magnitude and intensity that influence the duration, impacts, and warnings of the earthquake itself.

These groups of variables are oftentimes linked and, when combined, account for a sizable proportion of the injuries experienced during earthquakes. As for the U.S. ShakeAlert EEW system, these factors may also guide other national EEW networks in developing their own protective action messaging and campaigns specific to their cultural and social context, as well as their built environment.

Because recommendations will differ based on location and circumstance, lessons can be learned from the field of risk communication regarding how to build trust that recommendations are based on the best available knowledge and take into account the barriers that hinder people's abilities to take protective action. For communities to trust the system and the individuals promoting the protective action, communication is multidirectional, involves the public in discussions of risk, and acknowledges different elements of culture and risk tolerance (Ropeik and Gray, 2002; Sellnow et al., 2009; West et al., 2021). Furthermore, not all demographic groups are fully considered in the development of current recommended protective actions, such as pregnant persons, the unhoused, caretakers of children, and those with a high body mass index, among others (McBride et al., 2019). Involving underrepresented groups when developing recommendations is critical for effective and inclusive action.

Throughout our review of earthquake injury data, it is evident that scholars have adopted a wide range of methods to measure human behavior during an earthquake. Methods have ranged from using self-reported did you feel it data (Goltz et al., 2020b) and surveys after an earthquake (Vinnell et al., 2020) and analysis of primary injury medical data to infer behavioral responses (Johnston et al., 2014; Basharati et al., 2020), to analyzing closed-circuit television video footage of what individuals do during an earthquake (Lambie et al., 2016, 2017). Some studies measure demographic information and social context, whereas others do not. To develop a better understanding of what elements influence human behavior and outcomes during an earthquake, we need a comprehensive, coherent strategy for data collection. For example, Hemenway (2020) argues that we require better data collection for injury data that include updated computer systems and methods to record and share these data. We also think developing a standardized protocol that would capture social, cultural, and environmental conditions, demographic characteristics, and features of an earthquake in relation to various health outcomes could help to advance the field. Although the development of such a protocol is beyond the scope of this paper, it is an important avenue for future research.

LIMITATIONS

This work has particular limitations that we want to acknowledge. First, the earthquake injury and mortality data that we relied on for our analyses were collected by different researchers, across varying geographic and time contexts, and using a variety of methods and measures. For that reason, we were not able to draw on a single uniform data set with all variables present. At the same time, the results of the analyses are instructive in helping us to see patterns in terms of who is most likely to be injured and killed. There is no standard set of questions that earthquake injury studies asked, which means that some studies provided insights into actions that people were taking during and after shaking, which can impact people's injuries, whereas other studies did not. This suggests that a more strategic approach to collecting consistent data is required — an approach that includes contextual determinants of behaviors — if we are to fully understand protective actions and how to create contextually relevant recommendations, campaigns, and education. However, the postearthquake response period can be a chaotic time for many and data collection is not the priority for many medical practitioners or responders, nor should it be. As explored in Sanchez-Carrillo (1989), medical records and data collection were not the priority for the earthquake response in Mexico City. Ardagh et al. (2012) confirm that the hospital system in Christchurch during the 2011 earthquake also struggled. As such, sensitivity and compassion must also be considered for the injured and the responders.

Second, our goal in this paper was to link earthquake morbidity and mortality data to recommended protective actions. Put simply, we wanted to know if survival rates increased when people took the proper recommended protective actions. Due to the aforementioned limitations in the data, we were not always able to make this link. To fill this gap in our knowledge, we recommend that earthquake injury researchers include any protective actions taken in future studies. However, there is sufficient evidence, when accounting for earthquakes in the Western United States, for us to recommend DCHO as the primary recommended protective action in ShakeAlert-powered alerts because warning times are likely to be extremely limited. Critically, we acknowledge that although DCHO is recommended in the US, it may not be the safest protective action in all cases and for all nations. Considerations for infrastructure, as well as cultural appropriateness, are critical to providing protective action guidance for the ShakeAlert system.

Other areas of social science research are needed for EEW systems. Publics' trust and values of the system have been explored in Japan (Nakayachi et al., 2019) and in New Zealand (Becker et al., 2020). Replication of these two studies in other countries or regions that have or are considering EEW systems would be beneficial to track attitudes and perceptions of EEW. In terms of cost-benefit analysis, this has been explored in the United States. Specifically, how much Washington residents would pay for such a system was investigated in Dunn et al. (2016) and for California residents in Johnson et al. (2016). A comprehensive cost-benefit analysis was completed for Washington State in Bouta et al. (2020). These topics lie outside the scope of this paper; however, we suggest that continuation and further exploration of other research topics on how humans understand and interact with EEW systems would be advantageous to furthering our holistic understanding of this critical system.

CONCLUSION

In this paper, we posit guidelines for the inclusion of protective actions with EEW systems. We have reviewed death and injury data from earthquakes, earthquake protective action recommendations that are prevalent today, and the associated educational campaigns. We also outline key lessons from risk communication and other social science literature that are of relevance to the public communication portion of the rollout of ShakeAlert in California, Oregon, and Washington. Within this context, the literature suggests that DCHO is the best protective action for the ShakeAlert system to include in its warning message. In addition, developing messaging for specific demographic groups, combined with site-specific training to build procedural knowledge, can aid in the effective implementation of the EEW system. Finally, we recommend pathways forward for this interdisciplinary research community that explores EEW and discussed how there are remaining gaps in the literature that require further exploration. Consistency in collecting and reporting injury data globally may assist in aligning this fragmented literature to develop a richer understanding of how demographic, cultural, seismic, engineering, and technological issues can be addressed to reduce human suffering due to earthquakes.

Although the ShakeAlert system was predominantly developed by earthquake scientists, it is absolutely vital in moving forward that researchers from multiple disciplines be involved to ensure that what is ultimately a humanitarian tool concerned with improving life safety be placed in a broader context. This sort of boundary spanning, problem-focused, and solutions-oriented effort will ensure proper attention to the diverse publics who will ultimately integrate and use ShakeAlert in their daily lives as part of a larger toolbox of risk reduction tools.

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DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author.

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Biographies and photographs of the authors are not available.