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Great expectations for earthquake early warnings on the United States West Coast

Ann Bostrom[a,*], Sara K. McBride[b], Julia S. Becker[c], James D. Goltz[d], Robert-Michael de Groot[e], Lori Peek[f], Brian Terbush[g], Maximilian Dixon[g]

[a] Evans School of Public Policy and Governance, University of Washington, Seattle, WA, 98195-3055, USA
[b] United States Geological Survey, 350 N. Akron Road, Moffett Field, CA, 94035, USA
[c] Massey University, School of Psychology, Wellington, 6140, New Zealand
[d] Natural Hazards Center, University of Colorado Boulder, Boulder, CO, 80309-0483, USA
[e] United States Geological Survey, 525 S. Wilson Avenue, Pasadena, CA, 91106, USA
[f] Department of Sociology and Natural Hazards Center, University of Colorado Boulder, Boulder, CO, 80309-0483, USA
[g] Washington Emergency Management Division, Camp Murray, WA, 98430, USA

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ABSTRACT

In October 2019, California became the first state in the United States to fully activate a public earthquake early warning system—ShakeAlert®—managed by the U.S. Geological Survey. The system was subsequently rolled out in March 2021 in Oregon and May 2021 in Washington. Earthquake early warning (EEW) systems can provide seconds of notice to people and technological systems that shaking is imminent, but their effectiveness depends on recipients' expectations and actions as well as technical performance. To better understand these dependencies, we surveyed representative samples of adults in California (N = 1219), Oregon (N = 1020), and Washington (N = 1037) in February 2021. Most respondents had experienced earthquakes, but few had lived through violent shaking; most had not followed protective action guidance to Drop, Cover, and Hold On (DCHO) in earthquakes; and most reported no personal or social harm from prior earthquakes. Nevertheless, expectations and perceived usefulness of EEW were high, and higher still for those who expected alerts to be accurate and easy to use, expressed tolerance of missed and erroneous warnings, and expected to be affected by a damaging earthquake in their lifetime. Results suggest opportunities to better align public preferences and expectations with ShakeAlert operations. For example, some respondents preferred lower alerting thresholds than those proposed by government and scientists. Moreover, reported tolerance of warning errors was widespread, but respondents wanted explanations quickly, suggesting a need to further develop post-alert messaging. Findings from this study should be informative for future research on the co-evolution of experiences and expectations with EEW systems.

1. Introduction

This paper presents the results from a survey representative of populations in California (CA), Oregon (OR), and Washington (WA) in the United States (US). This research was conducted about the U.S. Geological Survey (USGS)-managed ShakeAlert Earthquake

* Corresponding author.
E-mail addresses: abostrom@uw.edu (A. Bostrom), smcbride@usgs.gov (S.K. McBride), J.Becker@massey.ac.nz (J.S. Becker), jamesgoltz@gmail.com (J.D. Goltz), rdegroot@usgs.gov (R.-M.-d. Groot), lori.peek@colorado.edu (L. Peek), Brian.Terbush@mil.wa.gov (B. Terbush), Maximilian.Dixon@mil.wa.gov.

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Early Warning System (a.k.a. ShakeAlert EEW system, ShakeAlert system, or ShakeAlert), to assess risk perceptions and expectations of earthquakes and EEW. It builds on previous work conducted on earthquake early warning systems in the Pacific Northwest from Dunn et al. [1] and Bouta et al. [2] before ShakeAlert was operational in the three US West Coast states.

ShakeAlert detects significant earthquakes so quickly that alerts can reach many people seconds to tens of seconds before shaking arrives.[1] The USGS—in partnership with state governments, universities, and private foundations—has been developing the ShakeAlert system for CA, OR, and WA since 2006; ShakeAlert-powered alerts to cell phones went live statewide in CA in October 2019 and then in OR and WA in March and May of 2021, respectively [3].

Warning systems work to the extent that they reduce damage, injury, loss of life, or emotional anxiety. As noted by the United Nations ([4]; p. v), "To be effective, early warning systems must be people-centered and must integrate four elements: (i) knowledge of the risks faced; (ii) technical monitoring and warning service; (iii) dissemination of meaningful warnings to those at risk; and (iv) public awareness and preparedness to act. Failure in any one of these elements can mean failure of the whole early warning system" (see also [5,6]). More recently, the National Academies of Sciences, Engineering, and Medicine ([7] p. 2) defined the purpose of alerts and warnings as follows: "… To provide the necessary information to warn the public and effect the necessary actions that will lead to their safety and to deliver the messages to populations at risk of imminent threats with the goal of maximizing the probability that people take protective actions and minimize the delay in taking those actions."

Recognizing the integral, integrated social elements of early warning systems—from the end users to the operators of these systems—is crucial for early warning systems to succeed [7–10]. While this recognition is not absent from ShakeAlert, the social science is nascent, especially when compared to the physical science investment in the development of this groundbreaking warning system. To progress this vital, potentially lifesaving multidisciplinary work, the research reported here develops a framework and survey design for assessing and informing further development of ShakeAlert, including future outreach, education, training, and technical engagement efforts. The survey results provide a baseline assessment of earthquake and EEW perceptions, experiences, and expectations, against which changes in expectations and responses to earthquakes and to EEW can be measured in the future. Our framework, research approach, and resulting findings are therefore relevant for those researching, developing, and making policies for EEW systems, as well as those engaged in outreach, education, training, and technical engagement efforts.

The schematic shown in Fig. 1 illustrates one way of thinking about EEW systems and how they can reduce the harms from earthquakes. It highlights the differing roles of scientists and professionals in *developing and operating* the system, in contrast to the roles of other individual and organizational decision makers whose *decisions and actions* the system is designed to inform. Two classes of decisions are highlighted in the schematic: the choices of warning algorithms and thresholds at which to warn, and the choices individuals, organizations and communities make to prepare for earthquakes or respond to them, which can be influenced by warnings. For example, in considering earthquake risk, scientists are responsible for where sensors should be placed, what they should measure, and how to assimilate collected data into algorithms to estimate shaking levels at various locations. Emergency management organizations are likely to be those who determine when an alert should be disseminated and how. Individuals and organizations make choices based on available knowledge and resources regarding the installation of warning apps or systems, and whether to drill warning responses.

The resultant actions taken emerge from decision makers' expectations of the hazard and warning system, which can vary depending on their roles and responsibilities in the warning ecosystem [12]. Diversity in perspectives can lead to conflicting expectations and preferences between system developers and technicians and end users. Further, in countries with multiple EEW systems there may be inconsistencies across systems, leading to additional conflicts in expectations [13]. While Fig. 1 shows that integrated warning systems begin with risk assessment, it does not reflect that they require public education to assure preparedness and knowing what to do when a warning arrives; indeed, public responses to warnings are the integrated outcome of public education, threat detection, and warning management ([11]; p. 31).

When they succeed, early warning systems for earthquakes and other hazards alert people and technical systems to impending events, allow time to engage in swift recommended protective actions, and ultimately reduce harm. Because they rely on detecting an earthquake in progress, EEW systems provide perhaps the least advance time of any such systems. Based on pressure waves (primary or *P*-waves) that precede more damaging shear or shaking waves (secondary or S-waves), EEW systems typically provide seconds to maximally minutes of warning that earthquake shaking is on the way. Further complicating efforts to warn the public, alerts sometimes arrive during shaking or after damaging shaking has commenced. While early performance of ShakeAlert has been promising in terms of warning lead time [12], complications such as late or missed alerts have the potential to disappoint public expectations and damage trust in the EEW system.

Prior research has examined the anticipated and experienced benefits of EEW systems in a range of geographic and cultural contexts [2,14,15], and the demand for and expectations of such systems (e.g,. [1,16]). EEW systems have varied in their efficacy. For example, in the 2017 Mexico City earthquake, the EEW system provided much less warning than people were used to and expected based on previous earthquake alerts [17]. The EEW system struggled notably for the M9.1 Great East Japan earthquake in 2011, miscalculating the size and location of the earthquake as well as suffering from regionally varying operational issues during the first 48 hours of its aftershock sequence due to higher seismic background noise and power failures [18]. Despite the challenges with the system, the majority of those polled in subsequent studies reported that the EEW system in Japan was useful [18,19]. It is worth noting, however, that five percent of respondents in one follow-up study in Japan did not want to receive any alert [19].

[1] Alerts delivered by third parties such as app providers are derived from a USGS-issued ShakeAlert Message, which is a data package that contains an estimate of the location, size (magnitude), and shaking intensity distribution for a given earthquake.

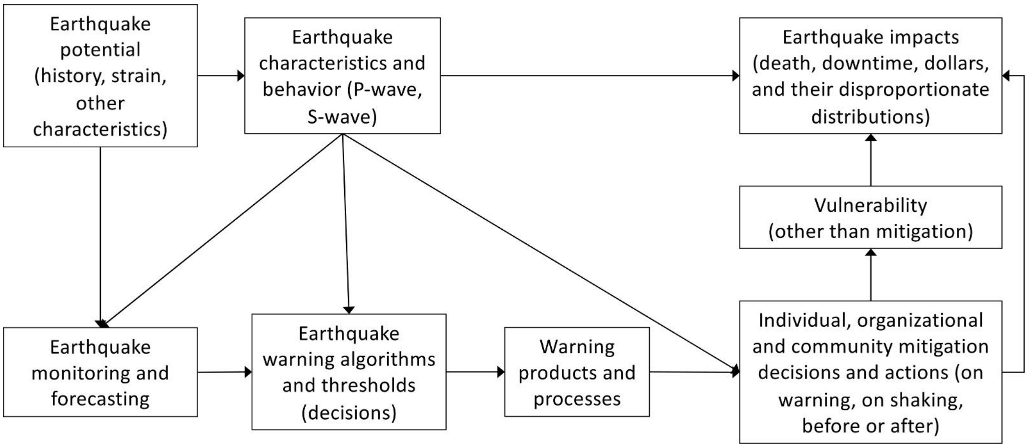

Fig. 1. Logic model for earthquake early warning (EEW) systems (adapted from Ref. [11]). This diagram depicts the elements (inputs, decisions, outputs, and outcomes) of integrated sociotechnical EEW systems.

Seismologists and emergency management officials often express concerns that false alarms and missed alerts might decrease interest in and responsiveness to warning systems [20]; see also [21,22]. In line with this, many have proposed that a successful earthquake early warning system, such as ShakeAlert, is one that alerts (only) for damaging earthquakes [23–27]. To assess the prevalence of these types of attitudes, expectations, and preferences, this study explores the expectations of potential warning recipients in CA, OR, and WA, along with their preferences, perceptions, attitudes, and knowledge of earthquakes and the ShakeAlert system.

The specific research questions that guided this study were:

- How do CA-OR-WA residents living in the US West Coast perceive the risks of earthquakes?
- What awareness and expectations do CA-OR-WA residents have of EEW, with regard to its behavior and its usefulness?
- What earthquake experiences have CA-OR-WA residents had that might inform their expectations of the system and preparedness actions?
- What preferences do CA-OR-WA residents have with regard to alerts, regarding alerting thresholds, content, and alert lead-time?
- How prepared are CA-OR-WA residents for earthquakes and to receive alerts?

These research questions were developed from prior research on earthquake early warning and the theories reviewed in section 2, with the pragmatic aim of evaluating the effects of EEW and informing EEW communication and education programs. Survey sampling and analysis methods are described in section 3. Findings in section 4 are presented in the following order: current awareness, knowledge, and expectations of EEW and ShakeAlert (4.1), previous earthquake experiences and expectations of future earthquakes (4.2), alerting expectations (4.3), and determinants of perceived usefulness of ShakeAlert and of interest in learning more about it (4.4). Section 5 explores alerting preferences, followed by discussion and limitations in section 6, and areas for future research and conclusions in section 7. The baseline results presented here provide an important foundation for future research, as the intention is to replicate this survey annually or bi-annually, to track changes in the populations of the ShakeAlert states over time.

1.1. Literature review

1.1.1. Earthquake early warning in context

Although "front detection" using alarm seismometers to detect shaking on railways had been employed since the 1960s in Japan [28], public earthquake early warning became operational first in Mexico City in 1991 following the 1985 Mexico Earthquake, which killed more than 10,000 people [17,29,30]. It took another decade and a half until a second public alerting system was released in Japan in 2007 [28]. Other major metropolitan areas and countries have followed suit in terms of offering public alerts, limited release alerts, and real-time testing and development of EEW systems, respectively. (Fig. 2).

1.2. EEW alerts and ShakeAlert

Currently ShakeAlert takes a multi-pronged alerting strategy as explained in Given et al. [24]; using a variety of channels such as smartphone apps, Wireless Emergency Alerts (WEAs) [31], and embedded smartphone operating systems (Google) to alert users of imminent earthquake shaking [3]. Channel preferences are also an important component in developing trust in messages, as described in Uses and Gratifications theory [32,33], which supports a multi-channel communication strategy for warnings. ShakeAlert aims to provide seconds of notice that potentially damaging earthquake shaking is imminent. Alerts delivered to people and automated systems may not be able to mitigate all damage [27], including deaths, injuries, and trauma, but may nevertheless provide enough time for people to take protective actions or mentally prepare themselves for the shaking to come [19].

As illustrated in Fig. 3, there are two thresholds for alerting the public via cell phones, as described in McGuire et al. [26]: (1) smart phone app providers and Google delivery via their Android operating system alerts for Magnitude (M) 4.5+ with intensity

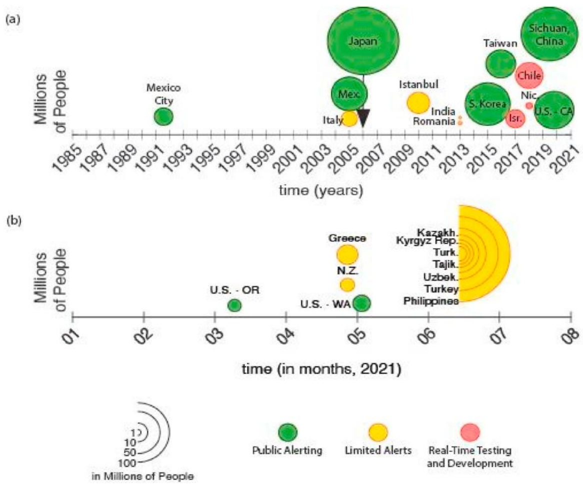

Fig. 2. The timeline of EEW rollout around the world: (a) for 1985 through 2020 and (b) for 2021, scaled by the millions of people to be potentially notified with an alert. The colors represent the various stages of EEW rollout: public alerting (green), limited alerts delivered to technical users and/or 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. 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. Reprinted from McBride et al. [3] with permission. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

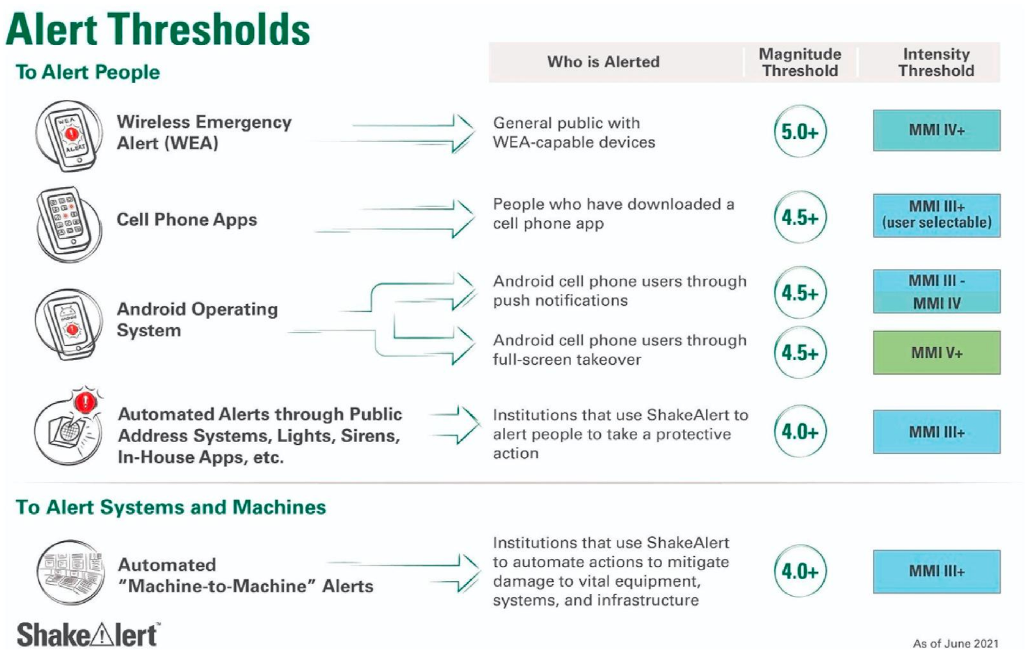

Fig. 3. Alerting thresholds for ShakeAlert, provided by the United States Geological Survey and reprinted with permission [34].

threshold of Modified Mercalli Intensity (MMI) III+ (weak shaking), and (2) the Integrated Public Alert & Warning System (IPAWS) system which generates WEAs for M5.0+ with MMI IV+ (light shaking) (Fig. 3).

In the United States, Google Android currently has bi-level alerting: "Be Aware" messaging, which does not include protective actions for earthquakes, and "Take Action" messaging, which includes Drop, Cover, and Hold On (DCHO) advice [3]. Bi-level alerting is determined by the MMI the person might feel; MMI III is the threshold for the "Be Aware" and the MMI V is the threshold for the "Take Action" alert [3]. The Japanese system, managed by the Japanese Meteorological Agency (JMA), has a form of bi-level alerting which alerts technical users at MMI 4.5 and the general public for MMI VI and higher [18] but only Google Android provides public bi-level alerting.

1.3. Protective actions and ShakeAlert

Protective actions advised in EEW messages vary depending on the geographic and cultural context [3], with some regions and countries offering explicit guidance about what protective actions to take—for example, DCHO or run outside—versus others that rely on sirens and do not suggest to users which actions to take. What it takes to trigger protective actions in a range of hazard and social contexts has been studied for decades; widely applied models include the Protective Action Decision Model (PADM) from Lindell & Perry [35]; Emergent Norm Theory as updated and described by Wood et al., [36]; and the Person Relative to Event approach [37], among others. More generally, warning response and risk communication insights are applicable, from both health (e.g. Refs. [38–44], and environmental behavioral domains, (e.g., Refs. [45–52]. Major elements of these models include experience, risk perception, self-efficacy, response efficacy, and trust, including trust in the warning itself as well as trust in the source of the warning or messenger (e.g., Ref. [53]; related to credibility, see Refs. [54,55]. Risk perceptions are broadly defined in the literature as both affective and cognitive, to include mental models of hazardous processes—i.e., causal beliefs about exposure to harm (sources and pathways), effects of exposures, and ways to reduce or avoid those effects (related to response efficacy or outcome expectancy)—as well as psychometrics such as perceived control, dread, familiarity, and subjective likelihood judgments.

In terms of earthquakes specifically, research has shown that past experience influences future preparedness actions (e.g., Refs. [56–58]. Efforts to simulate such experience include the Great ShakeOut, which promotes DCHO as the recommended protective action in response to shaking. Since 2008, the Great ShakeOut has been held annually and is now accompanied by detailed public education campaigns to encourage people in the United States [59] and globally [60] to take protective action and get prepared.

ShakeAlert advises DCHO as the best recommended protective action based on review of human behavior in response to shaking [61]. However, because the determination of which actions are likely to be most protective is a function of shaking, structural resilience, and the specific geological and geographical contexts, exposures, and response capacities of individuals at risk, it remains a topic of debate among emergency managers, engineers, and others in the United States and beyond [3].

1.4. Preparedness actions and knowledge research across CA-OR-WA

General earthquake preparedness knowledge studies are rare across the three focal states of CA, OR, and WA included in this study, although US national surveys suggest relatively low levels of perceived household emergency preparedness overall [62]. Results of a recent review [63] found few contemporary studies on this topic in the US. Rather, it is more common to find research that focuses on specific states [1,64,65] and local studies within states (e.g., Refs. [66–70]). Conglomerate surveys, such as the Federal Emergency Management Agency (FEMA) National Preparedness Survey [62], are nationally representative, but are not representative at the state level for the ShakeAlert states of interest in the present research.

In summary, while the current body of knowledge is rich in some aspects of our research questions, we focus on expectations as a key determinant of the success of early warning systems. Further, this research fills an important gap in knowledge about what people in ShakeAlert states expect from the system, from earthquakes, from themselves, and from the public officials managing this system.

2. Methods

2.1. Survey development and measures

The present study draws on much prior work including items from the TriNet studies and other US-based work [1,71–73] and studies from Japan [19] and New Zealand [16]. In addition, our baseline survey was reviewed and revised based on considerations introduced by the USGS ShakeAlert Joint Committee for Communication, Education, Outreach, and Technical Engagement and the Social Science Working Group (SSWG) [74]). The interdisciplinary SSWG[2] advised on the development, pretesting, and refinement of the survey items and instrument. Questions were developed with several theoretical and methodological considerations, including ease of implementation, post-event informativeness, and longitudinal comparisons. As noted, this baseline survey is intended to support future assessment of alert message content by exploring people's experiences and their reflections on specific alerts issued.

Survey questions were pilot tested in 2019 via Google Survey on an adult sample representative of internet users in WA state. Further revisions and pre-testing through the SSWG and a public sample of Lucid[3] panelists, managed by the National Opinion Research Center at the University of Chicago (NORC[4]) took place before the survey launch. The iterative process of survey co-design with the SSWG allowed for periods of data gathering, analysis, and reflection for purposeful refinement over several months.

All survey items are provided in Bostrom and Becker [75] (see Appendix 1) and referenced in the results section. Analyses and results focus on predictors of interest in and expectations of EEW (associations between these and experience, perceived risk, perceived efficacy (self and response) and usefulness of ShakeAlert, earthquake preparedness, and age and other household characteristics, to align with our research questions.

[2] The SSWG includes social scientists from a range of disciplines and career stages in academic positions, emergency management representation from Washington State Emergency Management Division, and representation from USGS ShakeAlert. The diversity of the SSWG shaped the survey formation in myriad ways. For example, emergency managers encouraged the exploration of preparedness as part of the survey, as well as assessing desired Modified Mercalli Intensity (MMI) thresholds for alerting.

[3] See https://luc.id/for a description of the Lucid sampling approach and how surveys are distributed to intended audiences. Accessed 5 June 2022.

[4] See https://www.norc.org/for more information on NORC, which was established in 1941 as an objective, nonpartisan research organization to advance social science and public opinion research. Accessed 5 June 2022.

2.2. Survey methods, sample, and analysis

The final web survey was fielded in CA, OR, and WA between February 17 and 27, 2021 (during the COVID-19 pandemic), through NORC. As indicated in the opening to the paper, ShakeAlert was available statewide in CA at the time the survey was released; rollout had been announced in OR and WA but the system was not yet publicly available statewide in the latter two states.[5] The survey took on average 7 min for respondents to complete. Respondents were paid a cash equivalent of $2 for completing the survey.

The sample included a general population sample of adults 18+ residing in each focal state (NORC AmeriSpeak panelists; CA n = 1219; OR n = 207; WA n = 317) combined with nonprobability opt-in online samples from Oregon and Washington (OR n = 813, WA n = 720, Lucid panelists), with TrueNorth calibration (based on small area estimation methods to explicitly account for potential bias associated with the nonprobability sample [76,77]), to yield more accurate population estimates for each state.

The weighted American Association for Public Opinion Research (AAPOR) Response Rate (RR)3[6] for the AmeriSpeak cumulative response rate was 4.68% (weighted AAPOR RR3 recruitment rate 19.52%, weighted household retention rate: 74.97%; survey completion rate 31.99%). For the combined CA-OR-WA sample, the study design effect is 3.413 and the study margin of error is ± 3.41% (the study design effect is 2.09 for CA, 1.628 for OR, and 1.471 for WA, and; the study margin of error is ± 4.37% for CA; ± 4.21% for OR; and ± 3.397% for WA). Analyses comparing states are calculated with state weights (CA N = 1219; OR N = 1020; WA N = 1037). Analyses across the CA-OR-WA region are calculated using a full sample weight for the combined general population of CA-OR-WA (N = 3726). Additional details on sampling, weighting calculations and the demographic profiles of the samples are provided in Appendix 2.

In addition to descriptive comparative analyses between the states, between those with and without awareness of ShakeAlert, and between those with and without earthquake experience, we conducted two regression analyses to examine whether perceived effectiveness and reliability of ShakeAlert predicted: (a) judgments of the usefulness of ShakeAlert, or (b) interest in learning more about ShakeAlert. Correlates of perceived usefulness of warning systems include the extent to which a system is perceived as enabling protective action (response efficacy) against a serious threat (perceived risk), as tempered by the perceived credibility or trustworthiness of the system (e.g., false alarm and missed alert rates) (e.g., [35,58]). Potential motivations for learning more about a warning system include these factors as well as perceptions of usefulness. Although some previous research suggests demographics are not predictive of hazard adjustments such as risk information seeking (e.g., [58,78]), other research on risk information seeking suggests demographics can have a small effect (e.g., [79,80]). We therefore controlled for demographics in these regressions.

3. Results

Results focus on the three states and illustrate differences between CA, which had the system operating for 18 months before the survey was administered, and OR and WA, which rolled out public alerting to cell phones in March and May 2021, after the survey data had been collected. This allowed us to compare those respondents who had experience with the system and with earthquakes in general to those with little or no experience with either earthquakes or the ShakeAlert system.

3.1. Awareness, knowledge, and expectations of ShakeAlert

Respondents were asked whether ShakeAlert was available in each of the three focal states. Fig. 4 compares the respondents in each of the three states who thought ShakeAlert was available in WA (top), OR (middle), or CA (bottom), by whether they reported having previously heard of ShakeAlert (25.3% in CA, 10.5% in OR, 10.8% in WA reported they had), or not. In all three states, the majority of respondents who had heard of ShakeAlert thought that it was available in their state, even though it was not available in WA and OR at the time of the survey distribution. California had the largest proportion of respondents (83.4% overall; 90.7% of the respondents who had heard of ShakeAlert before) who thought it was available in that state, which is correct.

To learn which agency people expect or trust to operate the system and who they expect to provide post-alert messaging about system performance, we asked respondents to indicate whether ShakeAlert "Is operated by the US Geological Survey." Respondents in CA who had heard of ShakeAlert were more likely to select that they knew this to be true (43.3%) than those in OR (26.3%), or WA (30.1%) (independent-samples proportions tests, $p < 0.05$). Slightly fewer—roughly a fourth of those in each of the three states—who had not heard of ShakeAlert before the survey selected this as their best guess (27% of those who had not heard of ShakeAlert in CA; 27.3% in OR, and 24.1% in WA).

Knowledge about the system overall was higher in CA than in WA and OR (Fig. 5). For example, Californians were more likely to recognize that ShakeAlert sends a warning that an earthquake is approaching, and that it does not predict earthquakes (i.e., they did not select this as a true statement about ShakeAlert), and that an alert might arrive after earthquake shaking starts. Very few respondents in any of the three states indicated that the system would confuse them (with responses ranging between 5% and 7%), would cause others to ask them for help (between 5% and 10%), or might be difficult to use (between 12% and 16%). About a fifth of respondents (WA 24%, OR 17%, CA 20%) thought it might be wrong or false.

Fig. 6 explores how people perceived ShakeAlert, based on whether they had heard of it or not. Across all three states, the ShakeAlert-aware more frequently selected correct descriptors of ShakeAlert than the ShakeAlert-unaware. In CA, fewer of the

[5] A ShakeAlert-powered Wireless Emergency Alert demonstration took place on February 25, 2021, in three counties (Pierce, King, and Thurston) in WA state. No major ShakeAlert news occurred in CA over the sampling period. In OR, the March 2021 rollout was imminent and was being reported on during the survey period.

[6] The specific response rate calculation for AAPOR Response Rate 3 can be found here: https://www.aapor.org/Education-Resources/For-Researchers/Poll-Survey-FAQ/Response-Rates-An-Overview.aspx Accessed 5 June 2022.

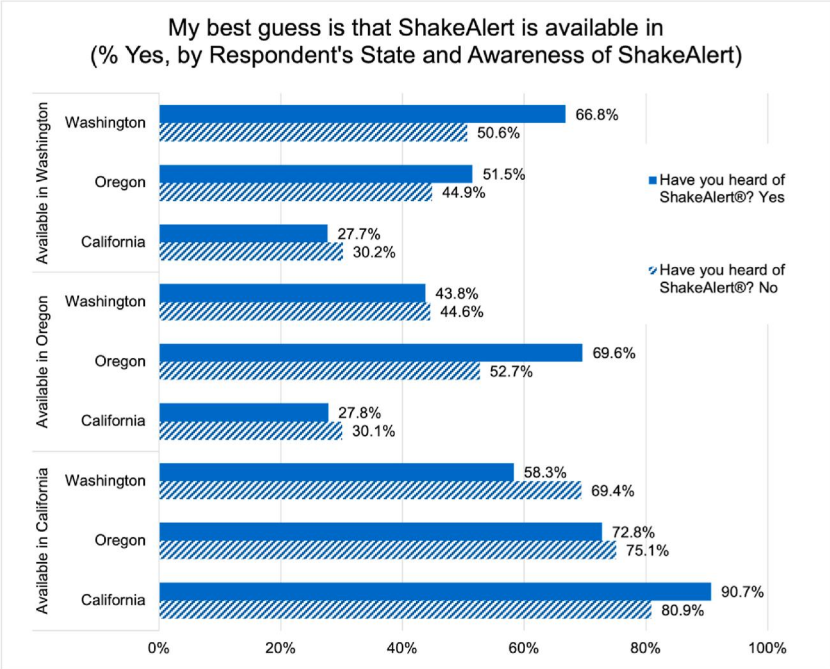

Fig. 4. Awareness of ShakeAlert among participants in the three states.

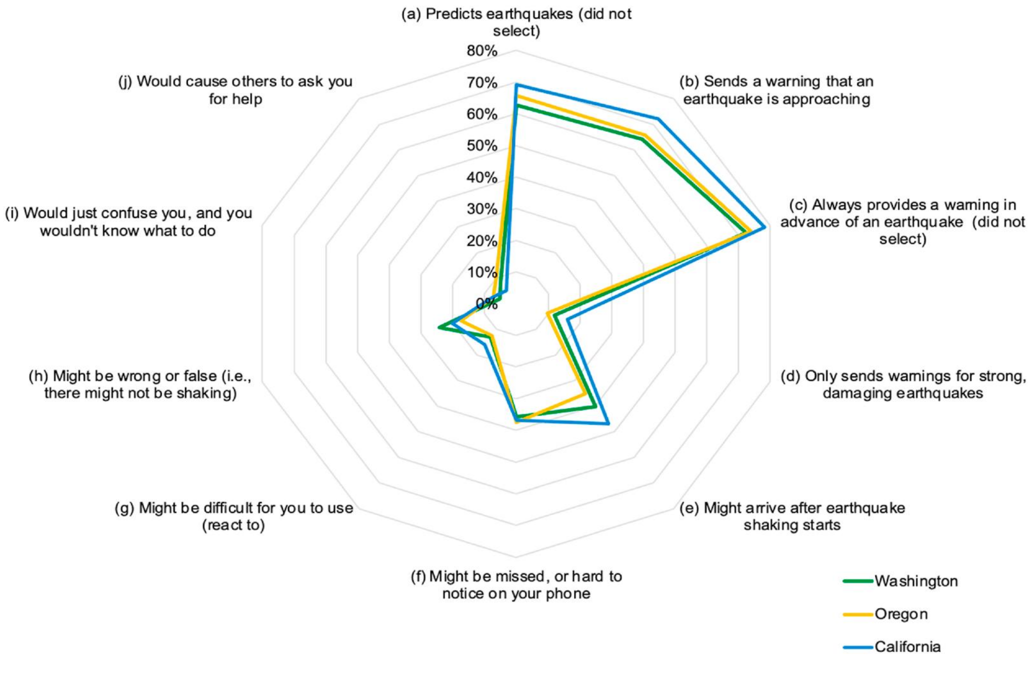

Fig. 5. Beliefs and expectations about ShakeAlert EEW, by state. Percentage of those responding yes to two select-all-that-apply questions: (a–d) "*Which of the following do you know to be true of ShakeAlert? [ShakeAlert is an earthquake early warning system that/My best guess is that ShakeAlert]" (note that a,c are misconceptions and are reverse-coded; the percentage of those who did not select a,c are reported)*; (e–j) "*If you had an app on your phone that could deliver alerts, do you think alerts:"*

ShakeAlert-aware thought that it predicted earthquakes (19%), as compared to the ShakeAlert unaware (35%) ($p < 0.001$, independent-samples proportion test), whereas in OR and WA, roughly a third thought this, regardless of ShakeAlert awareness status ($p > 0.05$).

Similarly, 25% of the ShakeAlert-aware in CA selected that ShakeAlert "only sends warnings for strong, damaging earthquakes" as compared to 14% of the ShakeAlert-unaware Californians and statistically indistinguishable low proportions of those in the other two

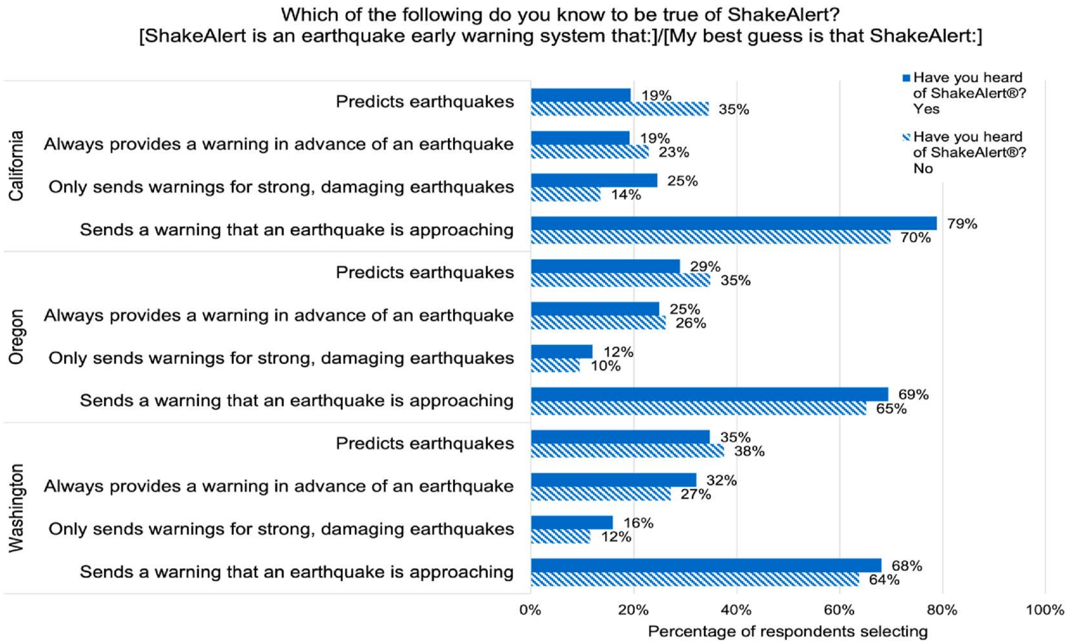

Fig. 6. Perceptions, attitudes, and knowledge of ShakeAlert by state and awareness of ShakeAlert, in response to: *Which of the following do you know to be true of ShakeAlert? [For those who reported having heard of ShakeAlert: "ShakeAlert is an earthquake early warning system that:"/For those who reported not having heard of ShakeAlert: "My best guess is that ShakeAlert:"].* Response Scale: *Please select all that apply.*

states (between 10% and 16%), regardless of their prior awareness of ShakeAlert. Despite this, majorities of respondents (over 60%) in all three states understood that ShakeAlert would send a warning that an earthquake was approaching, which is largely correct.

Respondents in all three states tended to agree (between 3.48 and 4.13 on a scale where "agree" was coded as 4 and "strongly agree" was coded as 5) that ShakeAlert would enable them to physically protect and mentally prepare themselves and help others. People in WA and OR, where ShakeAlert was not yet available publicly at the time of the survey, were more optimistic about what they could achieve and what information ShakeAlert could provide them when compared to Californians surveyed (Fig. 7).

The largest differences in expectations were between the ShakeAlert-aware in WA and OR as compared to the ShakeAlert-aware in CA. Of the ShakeAlert-unaware, expectations of usefulness were roughly equivalent across the three states for all questions asked (Fig. 7).

3.2. Previous experience and expectations of future earthquakes

As noted earlier, previous earthquake experience has been found to inform future actions [56], suggesting such experiences may play a central role in shaping expectations, behavioral intentions, and actual behaviors. Across the three states, 93.4% in CA, 79.4% in OR, and 80.7% in WA reported having experienced an earthquake. In all three states, the modal recent earthquake experience was mild shaking (corresponding to an MMI IV; 56% CA, 47.5% OR, 41.8% WA), with about a fourth of the sample (26% CA, 23.7% OR,

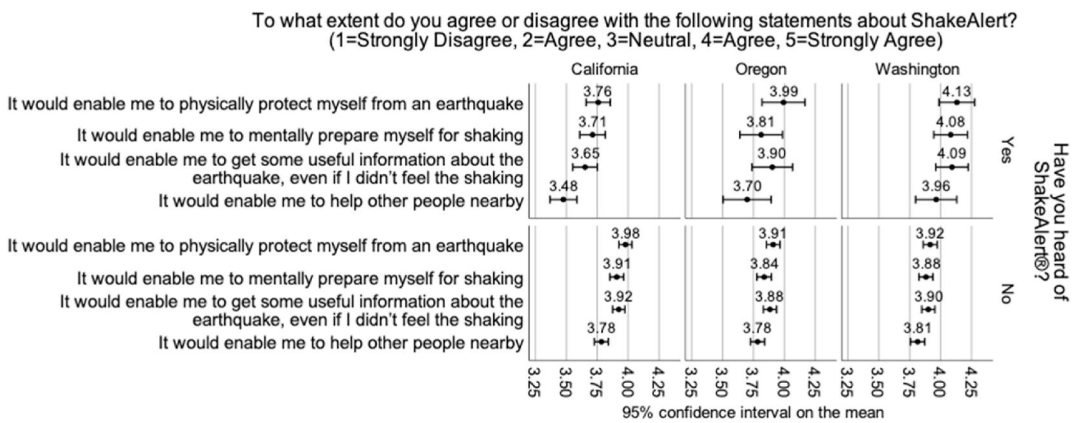

Fig. 7. Mean perceived usefulness of ShakeAlert, with 95% confidence interval on the mean, by state and by prior awareness of ShakeAlert *(Response scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly agree).*

23.2% WA) reporting having experienced weak shaking (corresponding to an MMI III). Moderate (MMI V), strong (MMI VI), or violent (MMI VI+) recent shaking experiences were marginally more commonly reported in WA than in OR, or CA (Fig. 8) (MMI V: CA 6.6%, OR 13.4%, WA 17.1%), (MMI VI + CA 10%, OR 14.5%, WA 16.9%). For those with earthquake experience, the average level of shaking experienced most recently was MMI IV or slightly higher. The average shaking levels experienced differed by state; these differences were small but statistically significant [$F_{(2,\ 2777)} = 19.4$, $p < 0.001$].

Reported harm experienced, which was not constrained to a specific experience or time frame, nevertheless correlated with the most recent shaking level experienced; 76% of those who had experienced mild shaking reported having experienced no injury, damage, or loss from earthquakes. Even among those who had experienced strong or violent shaking in their most recent earthquake experience, only 22% reported injury, damage, or loss to themselves personally, whereas 46% reported no injury, damage, or loss (Fig. 9).

Perceptions of earthquake risks varied somewhat across states. Those in CA were closer to agreeing that a damaging earthquake would occur in their city or town in their lifetime (3.73) than compared to 3.44 in WA and 3.25 in OR, where agree is coded as 4 and neutral as 3). This is likely because CA has experienced more damaging recent earthquakes (M6.9 Loma Prieta in 1989 and M6.7 Northridge in 1994), than WA with the 2001 M6.8 Nisqually, or OR, with relatively few damaging earthquakes. Notably the majority of respondents across the three states disagreed that a damaging earthquake in their state would not impact their lives (Fig. 10). In other words, majorities think it would affect their lives if there were a damaging earthquake in their state.

Actions taken previously and awareness of advice on how to respond to earthquakes and earthquake early warning are explored in Figs. 11 and 12. The typical response to the most recently experienced earthquake by respondents was not DCHO, but to stop what they were doing and stay put (Fig. 11). However, fewer of those who had experienced strong or violent shaking stopped what they were doing and stayed put (26.5% of those who experienced strong or violent shaking, N = 355, compared to 53% of those who experienced weaker shaking, N = 2360; Z = 10.31, $p < 0.001$), and relatively more of those who experienced strong or violent shaking reported DCHO (13%, compared to 6.8% of those who experienced weaker shaking, Z = 3.23 $p < 0.001$), standing in a doorway (25.4% vs. 13.5%, $p < 0.001$), or immediately leaving the building they were in (12.4% vs 5.2%, Z = 3.9, $p < 0.001$).

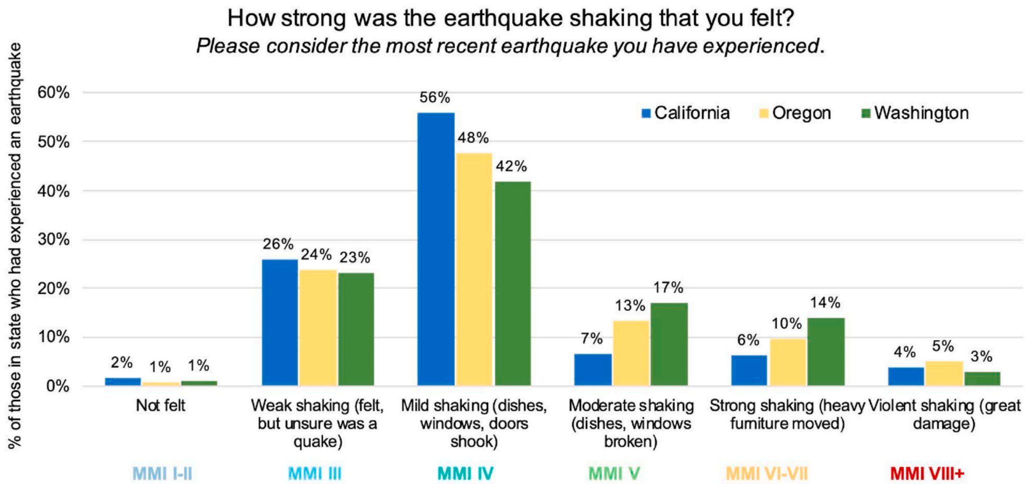

Fig. 8. Reported shaking felt for the most recent earthquake experience, by state, for those respondents with personal earthquake experience, multiple choice response.

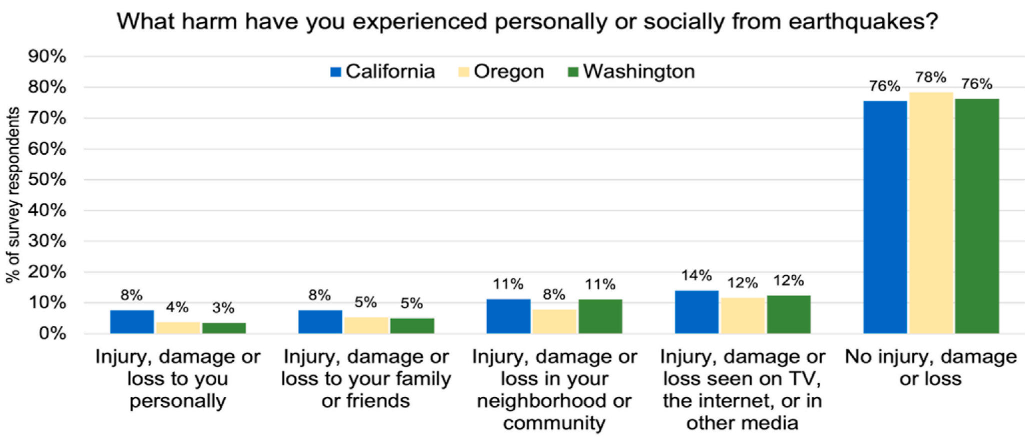

Fig. 9. Reported personal or social harm from earthquakes by state. Response scale: *Please select all that apply.*

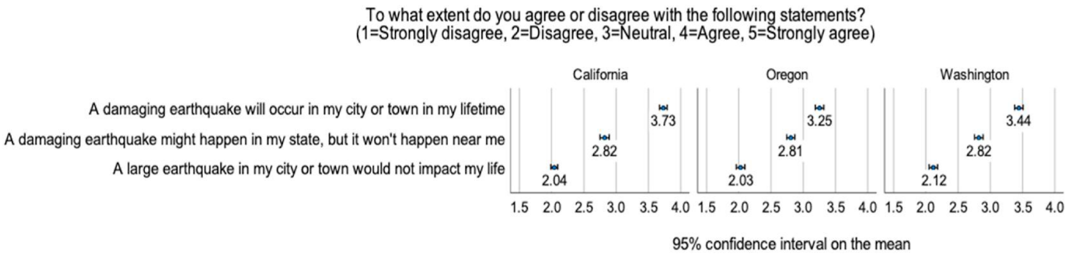

Fig. 10. Risk perceptions of participants as measured by responses to statements about earthquake expectations, by state.

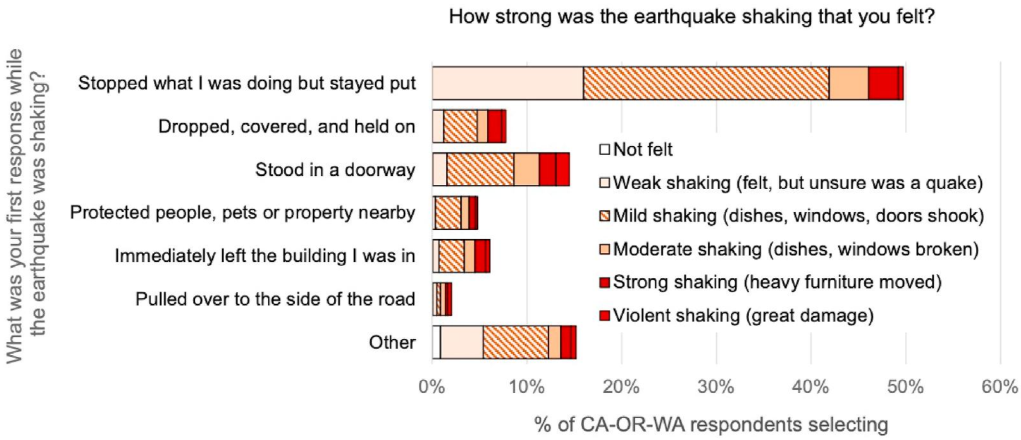

Fig. 11. Reported response to the most recently experienced earthquake, by perceived level of shaking experienced, for all respondents reporting earthquake experience across CA-OR-WA.

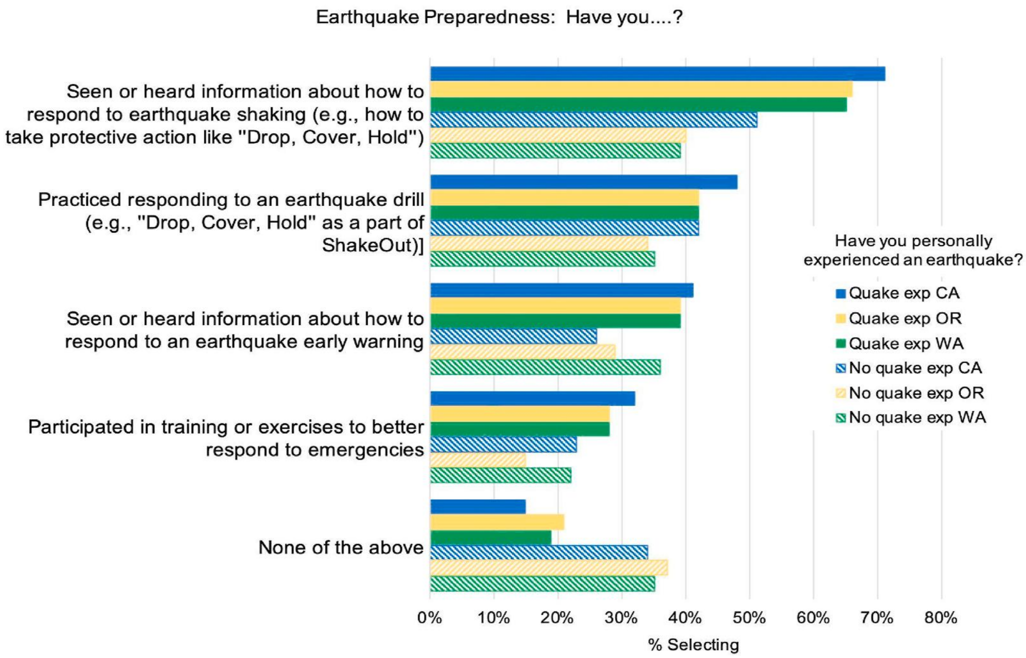

Fig. 12. Earthquake preparedness by state and by earthquake experience. Select-all-that-apply response scale.

California led in all earthquake preparedness actions except with regard to reporting about what they had seen or heard about how to respond to an earthquake early warning (differences between the three states were not statistically significant) (Fig. 12). This is notable as EEW had been available in the state of CA for almost 18 months at the time the survey was administered. The "none of the above" answer was almost equal in all three states for those who had no earthquake experience (approximately 30–35% of the respondents) compared to lower numbers for those who had earthquake experience previously (15–20%). This may indicate that either those respondents who had earthquake experience were motivated by their experiences to take action, or it is also possible that the earthquake experience of the location they lived in had prompted the availability of more earthquake preparedness activities in those areas. Awareness was similar in WA and OR for awareness and practice ($p > 0.10$ for independent proportion tests on all response options). In comparisons of CA to OR and WA, similar proportions had seen or heard information about how to respond to an earthquake early warning ($p = 0.07$), but higher percentages of respondents in CA than in WA and OR selected all other responses, and relatively fewer in CA selected none of the above ($p = 0.004$ for the CA vs WA and OR percentages who reported having participated in training to respond to emergencies, $p < 0.001$ for the remaining comparisons) (Fig. 12).

3.3. Alerting expectations

Expectations about false alerts and missed alerts varied little across the three ShakeAlert states, with the majorities in all three states stating that even if these would occur, the system would still be perceived as valuable. In order to determine tolerance for errors in system performance, we asked respondents if they would still want the system if it would sometimes issue false alerts or lead to missed alerts. We disaggregated the data based on those with earthquake experience and those without it; this revealed notably different attitudes and expectations towards the system.

We found respondents from all three states had a high tolerance for false (Fig. 13) or missed (Fig. 14) alerts, however this varied some depending on both experience of earthquakes as well as knowledge of earthquake early warning.

Those with the most earthquake experience had the highest tolerance for false alerts, with the highest percentages in CA, second to WA, and followed by OR. However, participants in WA who had no earthquake experience were as interested as those with earthquake experience in receiving alerts even if the system sometimes sends false alerts, while respondents in the other two states without earthquake experience were less interested. It is notable that a quarter of almost all answers were “don't know,” indicating that participants may not have felt they had enough information to make an educated choice.

As shown in Figs. 13 and 14, tolerance for missed alerts was even higher than tolerance for false alerts, with large majorities of respondents in all three states expressing an interest in receiving alerts even if some might be missed, regardless of their prior earthquake experience. Notably the highest was CA, where those with and without earthquake experience regarded alerts as equally valuable despite the possibility of missed alerts. Among those with no quake experience, WA participants were most likely to express disinterest in alerts if they knew missed alerts were a possibility compared to the other two states, while OR participants were more likely than those in the other two states to report that they didn't know if they would still want to receive alerts.

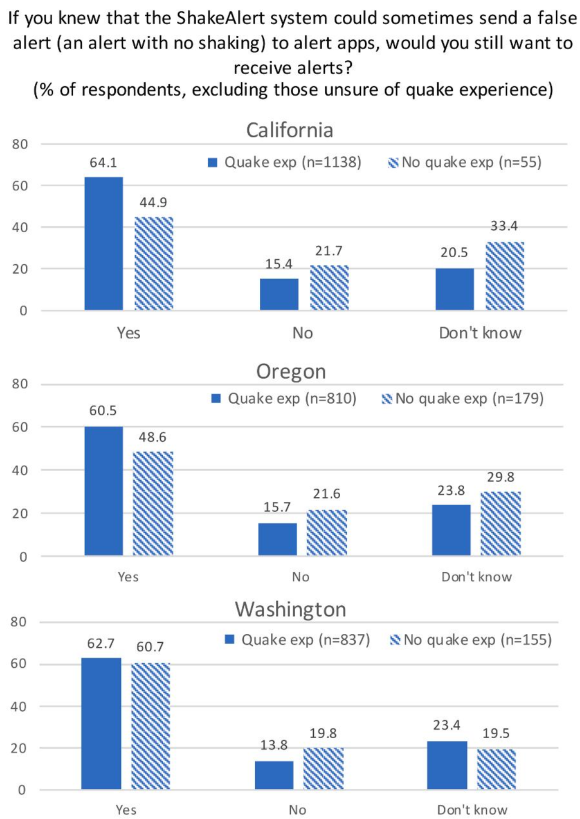

Fig. 13. Percentages of respondents reporting whether they would tolerate false alerts, by state, when asked if they would still want to receive alerts if the system sometimes produced false alerts.

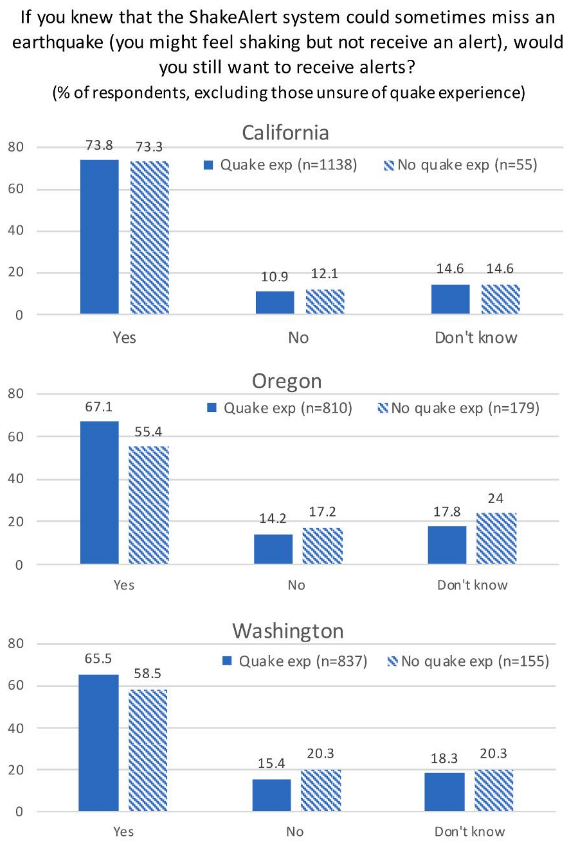

Fig. 14. Percentages of respondents reporting whether they would tolerate missed alerts, by state, when asked if they would still want to receive alerts if the system sometimes missed alerting for an earthquake.

3.4. Determinants of perceived usefulness of ShakeAlert EEW and interest in learning more

Regressing perceptions of the usefulness of ShakeAlert on these concerns can provide insights into how they are correlated, controlling for other possible explanations, such as awareness of ShakeAlert EEW, earthquake experience, perceived exposure to and risk from earthquakes (as measured by expectations of earthquakes in their area, and perceived personal or social injury damage or loss), gender, and age.

Fig. 15 presents the standardized coefficients (betas) estimated from regressing perceived usefulness of ShakeAlert on awareness of ShakeAlert and ShakeAlert functionality (model 1), alerting accuracy and ease of use (added in model 2), tolerance of missed alerts and false alerts (added in model 3), earthquake risk perceptions (added in model 4), and characteristics of the respondent and their household (presence of household members with disabilities or young children, age, race/ethnicity, gender, income, and state) (added in model 5). The dependent variable for this analysis is a single index of ShakeAlert usefulness calculated as an average of the four measures of usefulness shown in Fig. 7; it has high reliability (Cronbach's alpha = 0.86).[7]

Tolerance of missed (beta = 0.144) and false alerts (beta = 0.125) were most strongly positively associated with perceived usefulness of ShakeAlert, followed by identifying as Hispanic (beta = 0.123). Perceived usefulness also increased as a function of risk perceptions, such as whether or not respondents expected a damaging earthquake in their city or town in their lifetime (beta = 0.112), and if they thought a large earthquake in their city would affect them (beta = −0.07 on a large earthquake in my city or town would not impact my life), but also if they expected a damaging earthquake in their state but not near themselves (beta = 0.104), controlling for other variables in the full model (Fig. 15).

Understanding that ShakeAlert sends a warning that an earthquake is approaching was positively associated with its perceived usefulness (beta 0.076), but so was the misconception that it always provides a warning in advance of an earthquake (beta = 0.100) (Fig. 15, model 5). Unexpectedly, perceived usefulness of ShakeAlert was consistently lower for those who had heard of ShakeAlert (beta = −0.07), after controlling for other factors, suggesting that a lack of familiarity might be associated with greater optimism about system performance. As anticipated, perceived usefulness of ShakeAlert was higher for respondents who did not anticipate problems with alerts, as indicated by the negative coefficient (beta = −0.096) on “Might be difficult for you to use.” It was also higher for those who thought it might cause others to ask the respondent for help (beta = 0.085), higher for those in WA than those

[7] Principal components analysis [72] produced a single regression factor score that explains 70.6% of the total variance across these items, suggesting that using a single index is reasonable. The reliability analysis indicated that removing any one of the four items reduced the overall scale reliability.

DV: Perceived Usefulness of ShakeAlert (Average of Q7A, Q7B, Q7C, Q7D)		Model 1	Model 2	Model 3	Model 4	Model 5	p-value Model 5
	Have you heard of ShakeAlert®?	**-0.077**	-0.067	**-0.081**	**-0.090**	**-0.070**	**<0.001**
ShakeAlert is an earthquake early warning system that:/My best guess is that ShakeAlert:	**Predicts earthquakes**	**0.098**	**0.089**	**0.090**	**0.090**	0.057	0.005
	Sends a warning that an earthquake is approaching	**0.112**	**0.108**	**0.084**	**0.071**	**0.076**	**<0.001**
	Always provides a warning in advance of an earthquake	**0.154**	**0.150**	**0.124**	**0.123**	**0.100**	**<0.001**
	Only sends warnings for strong, damaging earthquakes	0.015	0.031	0.024	0.021	0.010	0.601
If you had an app on your phone that could deliver alerts, do you think alerts:	Might arrive after earthquake shaking starts		0.007	-0.026	-0.026	-0.019	0.419
	Might be missed, or hard to notice on your phone		-0.007	-0.003	-0.011	-0.011	0.623
	Might be difficult for you to use (react to)		-0.088	**-0.100**	**-0.103**	**-0.096**	**<0.001**
	Might be wrong or false (i.e., there might not be shaking)		-0.028	-0.033	-0.033	-0.033	0.115
	Would just confuse you, and you wouldn't know what to do		-0.027	-0.010	-0.010	-0.016	0.428
	Would cause others to ask you for help		**0.112**	**0.090**	**0.098**	**0.085**	**<0.001**
	None of the above		0.066	0.032	0.033	0.034	0.206
	If you knew that the ShakeAlert system could sometimes miss an earthquake (you might feel shaking but not receive an alert), would you still want to receive alerts?			**0.133**	**0.136**	**0.144**	**<0.001**
If you had an app and felt shaking, but had not received an alert, how do you think you would feel?	I would be annoyed			0.060	0.060	0.056	0.021
	I would be worried			0.059	0.058	0.038	0.097
	I would not care			-0.032	-0.030	-0.027	0.281
	I would be unhappy that I felt shaking			-0.005	0.000	0.000	0.984
	I would want to know immediately what happened			0.039	0.031	0.033	0.177
	I would remove the app from my device			-0.013	-0.011	-0.014	0.574
	If you knew that the ShakeAlert system could sometimes send a false alert (an alert with no shaking) to alert apps, would you still want to receive alerts?			**0.128**	**0.113**	**0.125**	**<0.001**
If you received an alert but felt no shaking, how do you think you would feel?	I would be annoyed			-0.017	-0.022	-0.022	0.375
	I would be worried			-0.001	0.000	-0.001	0.971
	I would not care			-0.036	-0.034	-0.029	0.287
	I would be unhappy that I received an alert when I did not feel any shaking			0.026	0.028	0.030	0.160
	I would want to know immediately what happened			-0.036	-0.039	-0.022	0.394
	I would remove the app from my device			-0.011	-0.010	-0.007	0.781
	Have you personally experienced an earthquake?				-0.006	0.026	0.197
What harm have you experienced personally or socially from earthquakes?	Injury, damage or loss to you personally				-0.054	-0.034	0.131
	Injury, damage or loss to your family or friends				0.005	0.003	0.889
	Injury, damage or loss in your neighborhood or community				-0.017	-0.022	0.382
	Injury, damage or loss seen on TV, the internet, or in other media				0.052	0.054	0.045
	No injury, damage or loss				-0.033	-0.036	0.290
To what extent do you agree or disagree with the following statements?	**A damaging earthquake will occur in my city or town in my lifetime**				**0.104**	**0.112**	**<0.001**
	A damaging earthquake might happen in my state, but it won't happen near me				**0.097**	**0.104**	**<0.001**
	A large earthquake in my city or town would not impact my life				-0.064	**-0.070**	**<0.001**
	Is there anyone in your household who has a disability requiring assistance from others?					-0.024	0.220
	Respondent age					**-0.083**	**<0.001**
	Number of Household members ages 0 to 5					0.018	0.363
Combined Race/Ethnicity (Reference: White, non-Hispanic)	Black, non-Hispanic					0.005	0.820
	Other, non-Hispanic					-0.009	0.638
	Hispanic					**0.123**	**<0.001**
	2+, non-Hispanic					0.036	0.070
	Asian, non-Hispanic					0.034	0.105
With which gender identity do you most identify? (Reference: Man)	Woman					0.060	0.003
	Transgender woman					-0.028	0.160
	Transgender man					-0.006	0.761
	Gender variant/non-conforming					0.030	0.117
	4-level Household Income					-0.043	0.035
State (Reference: CA)	**WA**					**0.093**	**<0.001**
	OR					0.055	0.023
	Adjusted R Square	0.064	0.088	0.148	0.167	0.197	
	F Change	31.828	9.441	12.232	6.389	6.641	
	(df1, df2)	(5,2236)	(7,2229)	(14,2215)	(9,2206)	(15,2191)	

Fig. 15. Regression of the average of four measures of perceived usefulness of ShakeAlert (1 = Strongly disagree, to 5 = Strongly Agree; see Fig. 7 for wording of these items) on predictors describing expectations of ShakeAlert and earthquake risk perceptions, controlling for demographics. Models were estimated as linear re-

gressions of the index of four usefulness variables (principal components analysis regression factor) on other variables, with a constant. Select-all-that-apply and multiple choice variables coded as 1 if selected, 0 if not. Data were weighted to represent the general publics aged 18+ across all three states (CA, OR, WA). Column values are standardized coefficients (betas). **Bolded p < 0.001**. All F-changes are significant at p < 0.01.

in CA (beta = 0.093), and higher for younger respondents (beta = −0.83 on respondent age). After controlling for other factors, neither personal or social experience of loss nor personal experience of an earthquake were predictive of the perceived usefulness of ShakeAlert.

About half (55.2%) of those in all three states expressed interest in learning more about ShakeAlert, slightly more in CA than in OR and WA. Fig. 16 shows the results of regressing interest in learning more about ShakeAlert on these potential explanatory factors. Those who reported having experienced no injury, damage, or loss from an earthquake, personally or socially, were less likely to be interested, while those who thought a damaging earthquake was likely to occur in their city or town in their lifetime were more likely to report interest in learning more. Those who thought an earthquake early warning would be useful, by helping them to protect themselves or others, and those who reported being tolerant of missed and false alerts were more likely to report being interested in more information about ShakeAlert. In contrast, those who thought alerts might be wrong or false were less likely to report an interest in learning more, after controlling for other factors.

4. Informing EEWS development on the US West Coast

To further inform EEWS development, the survey explored preferences for alerting channels, message content, how long people thought they would need to respond to an alert, and for what level of shaking they would prefer to be alerted.

4.1. Preferences for alerting channels, content, time to respond, and shaking thresholds

Trust is a critical component for people to respond to a message; they must first trust both the source and the channel. While across all three states there is an overwhelming preference to be alerted by cell phone or smartphone, 40% reported being interested in TV messages, and 30% in public announcements via a loudspeaker or siren, closely followed by an interest in radio messaging (Fig. 17). Preferences for smartphone alerts may be due to the immediacy, availability, or personal connection that people have with their mobile devices but could also be because this has become a dominant channel for alerting, given the rise of Wireless Emergency Alerts delivered to people's cell phones.

When asked what information they most wanted included in the alert, those who had heard of ShakeAlert preferred shaking intensity and time-to-shaking (Fig. 18). Those who had not heard of ShakeAlert preferred shaking intensity and recommended protective actions. However, all options ranked highly with relatively small differences between each. WEAs currently do not provide shaking intensity information [3].

When asked “What would be the minimum warning time you think you'd need to respond (i.e., between receiving the alert and feeling the shaking?)” almost half reported that they would need more than 30 s to respond (24% selected 31–60 s, 22% selected more than minute) (Fig. 19). In all three states, the majority of respondents answered they would need a minimum warning time of 30 s. However, in CA, 15% of respondents suggested that they could take action within 6–10 s; largely the respondents in that state suggested that they could take action with less notice than the respondents in the other two states. Oregon participants suggested they needed the longest warning times but also reported the highest amount of uncertainty about how much time they would need.

When the respondents were asked in an open-ended question in the survey what they would do if they were indoors and knew that they had 10 s of alerting time, prevalent words included, for example: get (342 mentions), cover (204), doorway (189), under (182), outside (126), safe (102), table (116), door (76), stand (75), take (74), move (65), drop (56), duck (38), protect (32), dog (28), time (27), and alert (23), among other words (Fig. 20). These words often showed up in action phrases like “Grab dog and run outside.” Typical responses for “get” include: “Get under a table or desk,” “Get under a table if possible or in a doorway if faster,” and “Get outside.” Most typical for “take” is the phrase “take cover.” “Time” showed up in contexts like “Not enough time to really do anything” and “I wouldn't even have time to check the phone after the alert.” Assessed here informally as a word cloud, the open-ended responses appear to support the closed-ended response categories used to assess responses to prior earthquakes discussed in section 4.2 (Fig. 11) and suggest that while there is some sensitivity to time limitations, considerable optimism prevails regarding the actions afforded by earthquake early warnings.

Alerting threshold preference—in terms of the lowest level of shaking that participants think would be useful to be warned for—is a key issue to understand, both in terms of system performance as well as trust in the EEW system. Approximately 62% of respondents thought alerts for weak or mild shaking would be useful, with 32% reporting that alerts only for higher shaking levels would be useful (Fig. 21). Five percent indicated that alerts even with no shaking felt would be useful, while one percent indicated only alerts for violent shaking would be useful.

4.2. Post-alert messaging

The survey also asked respondents about their preferences for post-alert messaging in the event of an earthquake as well as in the case of a missed or false alert. Because this question hinges on alerts, results are shown by awareness of ShakeAlert in Fig. 22. Interest in knowing immediately what happened was high for both missed and false alerts (over 40%), though slightly higher (on average 4.4%) for missed alerts than for false alerts. About a third overall (32.2%; 33% of the ShakeAlert-unaware; 31% of the ShakeAlert-aware) thought they would be annoyed over a missed alert, while only a fourth overall (23.8%; 25% of the ShakeAlert-unaware, 21% of the ShakeAlert-aware) thought they would be annoyed about a false alarm. More reported thinking they would be worried after a

Dependent Variable: Are you interested in learning more about ShakeAlert? (No=0, Yes=1)

	B	S.E.	Wald	df	Sig.	Exp(B)
What harm have you experienced personally or socially from earthquakes?						
Injury, damage or loss to you personally	0.16	0.253	0.4	1	0.529	1.173
Injury, damage or loss to your family or friends	-0.24	0.247	0.94	1	0.331	0.787
Injury, damage or loss in your neighborhood or community	-0.683	0.218	9.77	1	0.002	0.505
Injury, damage or loss seen on TV, the internet, or in other media	-0.09	0.212	0.18	1	0.671	0.914
***No injury, damage or loss**	**-0.918**	**0.213**	**18.6**	**1**	**<.001**	**0.399**
To what extent do you agree or disagree with the following statements?						
***A damaging earthquake will occur in my city or town in my lifetime**	**0.187**	**0.053**	**12.5**	**1**	**<.001**	**1.205**
A damaging earthquake might happen in my state, but it won't happen near me	-0.083	0.045	3.4	1	0.065	0.92
A large earthquake in my city or town would not impact my life	-0.097	0.053	3.35	1	0.067	0.908
Have you heard of ShakeAlert®?	-0.382	0.125	9.36	1	0.002	0.682
Which of the following do you know to be true of ShakeAlert? ShakeAlert is an earthquake early warning system that:/My best guess is that ShakeAlert:						
Predicts earthquakes	-0.023	0.115	0.04	1	0.845	0.978
Sends a warning that an earthquake is approaching	0.171	0.114	2.24	1	0.135	1.187
Always provides a warning in advance of an earthquake	-0.096	0.131	0.53	1	0.465	0.909
Only sends warnings for strong, damaging earthquakes	0.382	0.146	6.85	1	0.009	1.465
Is operated by the U.S. Geological Survey	0.347	0.119	8.56	1	0.003	1.415
Is operated by a private company	-0.037	0.153	0.06	1	0.807	0.963
***Usefulness_Avg**	**0.528**	**0.081**	**42**	**1**	**<.001**	**1.695**
If you had an app on your phone that could deliver alerts, do you think alerts:						
Might arrive after earthquake shaking starts	0.053	0.124	0.18	1	0.670	1.054
Might be missed, or hard to notice on your phone	-0.206	0.122	2.87	1	0.090	0.814
Might be difficult for you to use (react to)	0.201	0.15	1.79	1	0.181	1.222
***Might be wrong or false (i.e., there might not be shaking)**	**-0.513**	**0.129**	**15.8**	**1**	**<.001**	**0.599**
Would just confuse you, and you wouldn't know what to do	0.69	0.221	9.73	1	0.002	1.994
Would cause others to ask you for help	0.328	0.227	2.09	1	0.148	1.388
None of the above	-0.129	0.164	0.62	1	0.430	0.879
***If you knew that the ShakeAlert system could sometimes miss an earthquake (you might feel shaking but not receive an alert), would you still want to receive alerts?**	**0.667**	**0.184**	**13.2**	**1**	**<.001**	**1.949**
If you had an app and felt shaking, but had not received an alert, how do you think you would feel?						
I would be annoyed	-0.436	0.14	9.67	1	0.002	0.647
I would be worried	0.406	0.139	8.46	1	0.004	1.500
I would not care	-0.281	0.168	2.79	1	0.095	0.755
***I would be unhappy that I felt shaking**	**0.643**	**0.167**	**14.8**	**1**	**<.001**	**1.902**
I would want to know immediately what happened	-0.004	0.13	0	1	0.976	0.996
I would remove the app from my device	0.214	0.245	0.77	1	0.382	1.239
***If you knew that the ShakeAlert system could sometimes send a false alert (an alert with no shaking) to alert apps, would you still want to receive alerts?**	**1.058**	**0.166**	**40.7**	**1**	**<.001**	**2.879**
If you received an alert but felt no shaking, how do you think you would feel?						
I would be annoyed	-0.021	0.158	0.02	1	0.893	0.979
I would be worried	0.151	0.156	0.94	1	0.332	1.164
I would not care	0.235	0.155	2.3	1	0.129	1.265
I would be unhappy that I received an alert when I did not feel any shaking	0.006	0.166	0	1	0.970	1.006
***I would want to know immediately what happened**	**0.507**	**0.14**	**13.2**	**1**	**<.001**	**1.661**
I would remove the app from my device	-0.35	0.33	1.12	1	0.289	0.705
With which gender identity do you most identify?	-0.174	0.064	7.51	1	0.006	0.840
Is there anyone in your household who has a disability requiring assistance from others?	0.006	0.008	0.45	1	0.503	1.006
Do you have earthquake insurance?	-0.016	0.009	3.11	1	0.078	0.984
Respondent age	-0.003	0.003	0.71	1	0.400	0.997
Household Income	-0.033	0.012	7.71	1	0.005	0.967
Number of Household members 0 to 5 years	0.005	0.21	0	1	0.981	1.005
***Combined Race/Ethnicityreference case is White, non-hispanic**			**26.2**	**5**	**<.001**	
Combined Race/Ethnicity Black, non-Hispanic	**-0.893**	**0.246**	**13.1**	**1**	**<.001**	**0.409**
Combined Race/Ethnicity Black, non-Hispanic	0.184	0.453	0.17	1	0.684	1.202
Combined Race/Ethnicity Hipanic	0.079	0.13	0.37	1	0.542	1.082
Combined Race/Ethnicity 2+, non-Hispanic	-0.231	0.295	0.61	1	0.435	0.794
Combined Race/Ethnicity Asian, non-Hispanic	0.493	0.175	7.92	1	0.005	1.637
***State (WA, OR, CA) reference case is CA**			**21.4**	**2**	**<.001**	
***State WA**	**-0.565**	**0.149**	**14.3**	**1**	**<.001**	**0.568**
***State OR**	**-0.652**	**0.188**	**12.1**	**1**	**<.001**	**0.521**
Constant	**-1.905**	**0.549**	**12**	**1**	**<.001**	**0.149**

Binary Logistic regression, data weighted to represent the general 18+ population of all 3 states together (WA, OR, CA).
Chi-square 652.768, 50df, p<0.001; -2 Log Likelihood 2520.422, Nagelkerke R-sq 0.326; 75.1% of observations predicted correctly.

Fig. 16. Regression of interest in learning more about ShakeAlert on: earthquake experience; perceived risk; awareness, knowledge and perceived usefulness of ShakeAlert; expectations of ShakeAlert and EEWS, including expected responses to missed and false alerts; and demographics. The dependent variable was coded as 1 if the respondent selected that they would like to learn more about ShakeAlert, 0 otherwise.

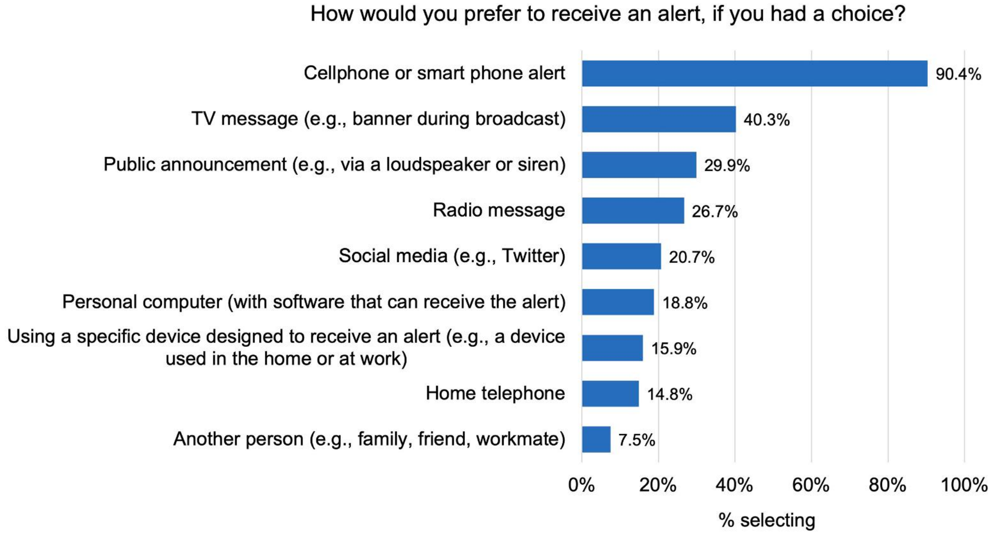

Fig. 17. Preferences for alerting channels, across all three states. Select-all-that-apply response scale.

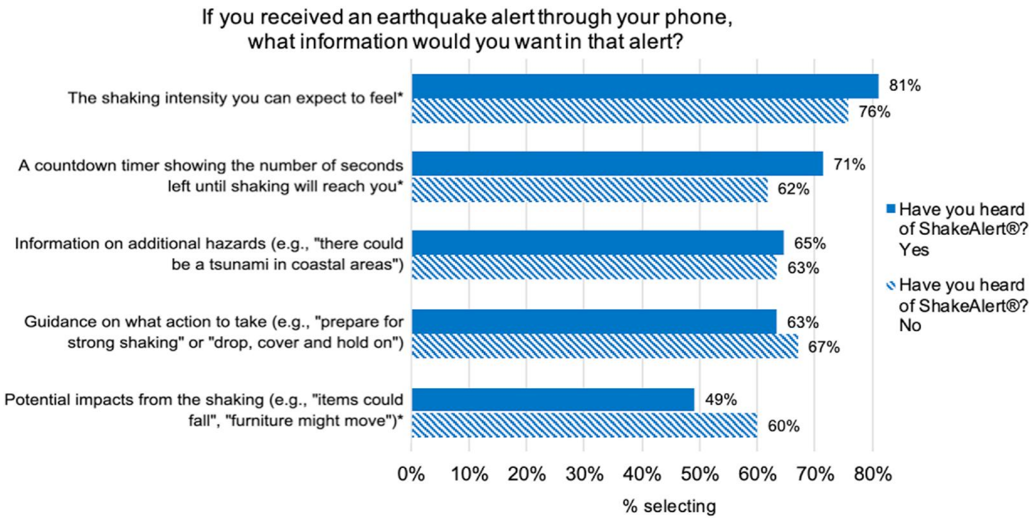

Fig. 18. Content respondents would want in an earthquake alert received through their phone, by prior awareness of ShakeAlert, across all three states.

missed alert (25.9% overall; 27% of the ShakeAlert-unaware; 24% of the ShakeAlert-aware) than after a false alert (18.1% overall). With the exception of unhappiness, all other observed differences between reactions to missed and false alerts in Fig. 22 are significant at $p < 0.01$ (paired-sample proportion tests).

Most of the differences by awareness of ShakeAlert, were small and unreliable, with a few notable exceptions. For missed alerts, "remove the app from my device" differed significantly by awareness of ShakeAlert ($p < 0.01$), with more of the ShakeAlert-unaware reporting that they would remove the app (12%) than the ShakeAlert-aware (7%). For false alarms, only "I would not care" differed significantly by awareness of ShakeAlert, with those who have heard of ShakeAlert more likely to have selected that they would not care (38%) than those who have not (31%) ($p < 0.01$, independent proportions test).

With participants ranking highly the desire to know why a false or missed alert occurred, this supports the argument made in McBride et al. [12] regarding the critical importance of post-alert messaging and information about system performance.

5. Discussion

Our results focus on knowledge of what the ShakeAlert EEW System does, knowledge regarding who operates the system, perceived status of ShakeAlert alerting in various states, and expectations of the system overall. We disaggregated the data by state and

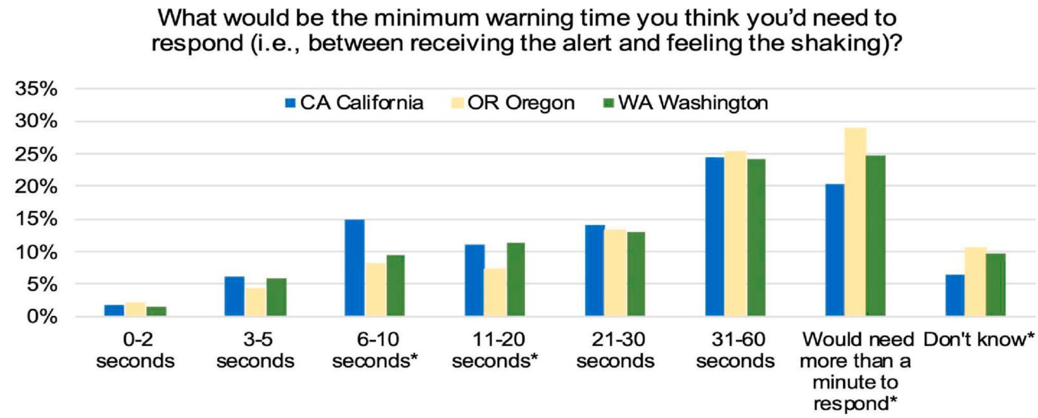

Fig. 19. Minimum warning time survey respondents reported needing to respond, by state. **At least one of the states differed from the other two at* $p < 0.05$ *in pairwise tests of state proportions.*

Fig. 20. Open-ended responses from CA-OR-WA in response to "What would you do if you were indoors and you knew you had the following alerting time? [10 s]." Generated using [96] with size proportional to frequency, including stemming, and excluding words that only appeared once, as well as *the, and, or, in, from, to, of, for,* and numbers.

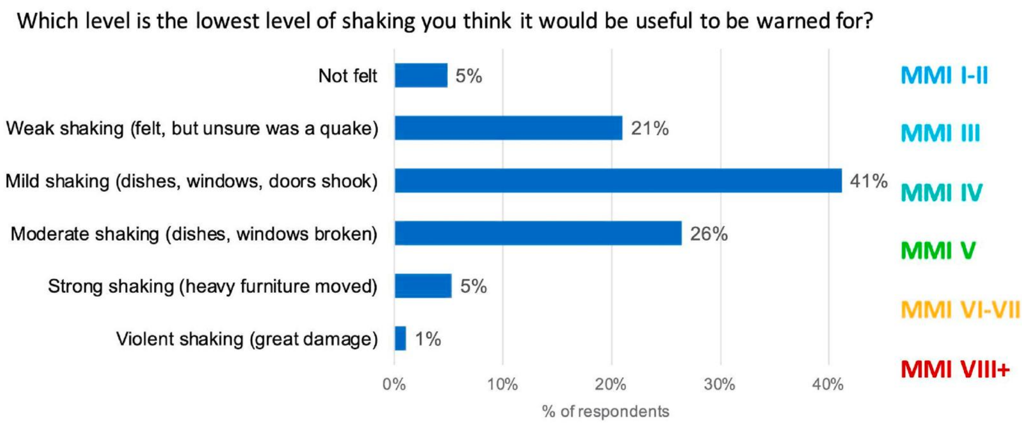

Fig. 21. Perceived usefulness of alerting thresholds across all three states (N = 3275).

earthquake experience to examine variations in experience, risk perception, self- and response efficacy, and awareness of and trust in the warning system, assessed through expectations of ShakeAlert performance and judgments of its usefulness. This study represents the first cross-state comparative research in the US regarding the implementation of EEW systems in the three ShakeAlert states of CA, OR, and WA.

This research—which builds upon prior work in other national contexts—explored what perceptions, attitudes, and knowledge people in the focal states in the Western US have about earthquakes and earthquake early warning systems, and how these in turn correspond to expectations for ShakeAlert. The analysis reviewed differences by region, earthquake experience, and knowledge of

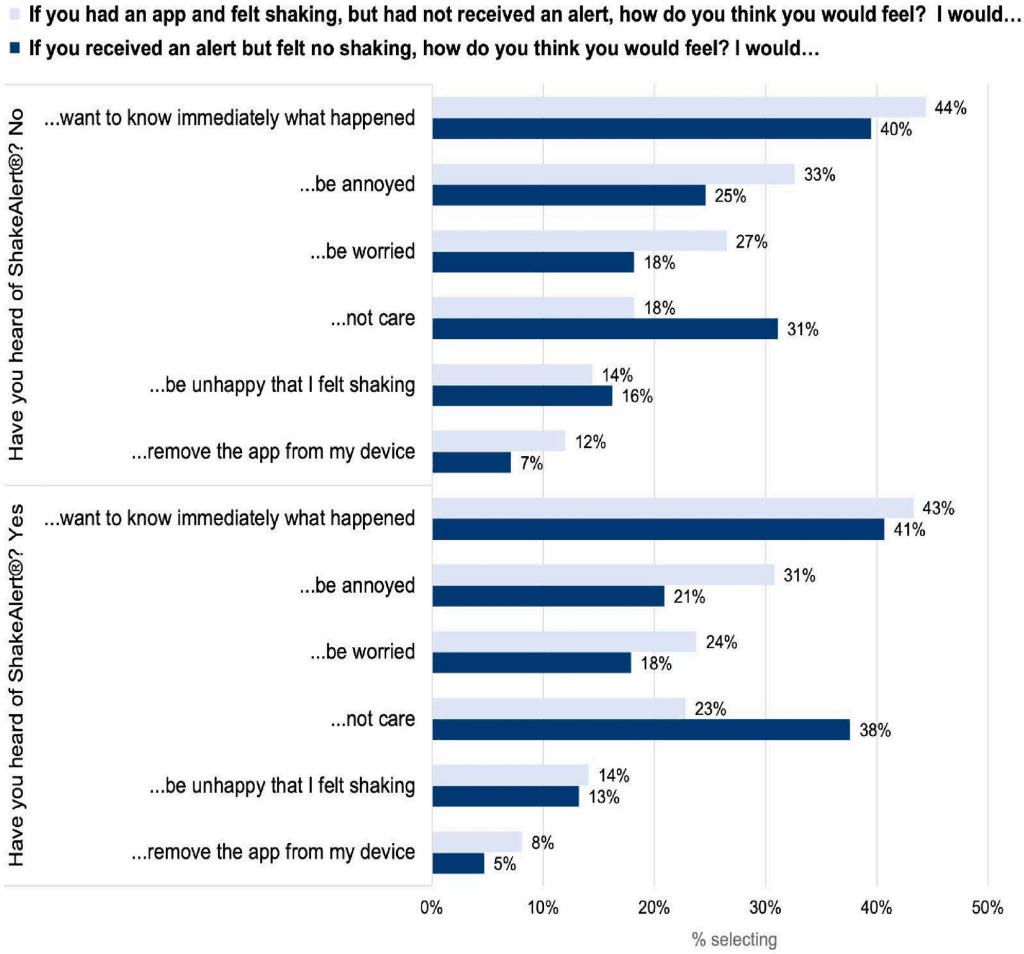

Fig. 22. Anticipated reactions to missed alerts (felt shaking but had not received an alert is in pale blue) and false alarms (received an alert but felt no shaking is in dark blue) across all three states, by awareness of ShakeAlert (top: No, have not heard of ShakeAlert; bottom: Yes, have heard of ShakeAlert). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ShakeAlert that, in turn, have shaped varying expectations of the system and of the impacts of future earthquakes, as well as other key outcomes as described in this concluding section. Taken together, these study findings contribute to a better understanding of the potential role of earthquake early warning systems relative to other influences on protective action decision making.

5.1. Regionalized differences: how people conceptualize EEW in OR and WA versus CA

Overall, we found that respondents in CA had more knowledge about the system, the protective actions to take when receiving an alert, and what types of earthquakes they would be alerted for. This finding aligns with the state of ShakeAlert at the time of data collection; CA was the only state where ShakeAlert-powered alerts were available statewide for delivery to cell phones. In addition, when compared to WA and OR, CA has stronger building codes and a longer history of damaging earthquakes, which likely heightened attention to the ShakeAlert system itself.

Of particular interest, in terms of best practice recommended protective actions [3], is the absence of DCHO responses by respondents in all three states. Drills have proven to be useful in encouraging people to take proper protective actions during earthquakes [81]. Given this, it may be helpful in the future to consider specific drills for ShakeAlert that include a test alert as well as encouraging people to take protective action as part of the drill.

5.2. Role of time/experience from rollout versus pre-rollout of ShakeAlert-powered alert delivery to cell phones

As noted previously, when this survey was disseminated, CA was the only state where ShakeAlert-powered alerts were being delivered to cell phones (via apps and WEAs) for imminent shaking. Yet even though ShakeAlert had been available for 18 months at the time of the survey, CA respondents were only slightly more likely than their counterparts in the other two states to express an awareness of the warning technology. Moreover, in all three states, respondents expressed a lack of knowledge about ShakeAlert overall and who manages the system (US Geological Survey), although those in CA, where the system was already active, had an almost 10% point advantage over those in OR/WA, where it was not.

5.3. Expectations

The survey asked a number of questions about what people can expect of themselves, given the amount of warning time that they think ShakeAlert can provide, what they expect from the ShakeAlert system and, in turn, the scientists and agencies that manage that system as well as what they can expect from the earthquake itself.

It appears from our survey that about a fourth of respondents, particularly in WA and OR, want alerts for any earthquake they may feel, and two-thirds of respondents expressed interested in alerts for MMI IV or lower. This means even small earthquakes are deemed by some to be alertable by the system. While alerting for small earthquakes may be difficult technically, the desire a fifth of respondents expressed to be alerted for weak shaking (MMI III), and 40% expressed to be alerted for mild shaking (MMI IV) may be due to the novelty of the system and that many people in the Pacific Northwest (PNW) of the US have reported either not feeling earthquakes ever or not having felt them in a long time. In the Becker et al. [16] study, people in New Zealand wanted to be warned for comparatively higher shaking intensities (MMI V-VI); a similar finding was found in Japan, where they have had EEW since 2007 [19]. These findings may be reflective of the many felt and damaging earthquakes that New Zealand and Japan have experienced in the last 15 years, including the M6.2 Christchurch earthquake, the M7.8 Kaikoura earthquake, and the M9.0–9.1 Great East Japan Earthquake, among others [82–84]. This may indicate that over time and with more alerts, expectations may shift to reflect the preferences of scientists as explained by Minson et al. [27], to alert only for potentially damaging shaking.

Another expectation we found regards what people expect of themselves and think they can achieve with the alert time. Our respondents expressed a degree of optimism related to taking personal protective actions and helping others, particularly given that many alerts will only provide a few seconds of warning. Given the limited time, people may be unable to complete many of the actions they identified in the survey. Likewise, participants in [16], like those in our study, were relatively confident in their own abilities to respond to earthquakes, which may be an indicator of optimism bias. A potential contributor to this optimism about alerts may have to do with overestimating how much time alerts are likely to provide. While we did not ask respondents to estimate this, their optimism suggests overestimation. Consider, for example, that had the ShakeAlert system been publicly alerting in the 2019 Ridgecrest earthquakes, alerts would have been issued to the system 7.5 s and 8.2 s after the earthquake originated, respectively [20,85].[8] With optimal application of a different algorithm (PLUM), it has been estimated that the system could have provided about 20 s of warning time [86]. However, the LA City-developed app at the time used MMI IV for its alerting threshold, when the Ridgecrest earthquakes occurred and, as the app did not deliver alerts outside LA County, no one was notified of the earthquake. Notably, even with PLUM, this is still <u>less</u> time than a majority of survey respondents thought they would need to take various protective actions to help themselves and others.

An additional potential issue is that people may be familiar with EEW systems in other countries, like Mexico City or Japan, where longer warning times have been showcased in video and media. Mexico City, in particular, has longer warning times due to the fact that the majority of damaging earthquakes originate relatively far from the city. Another consideration is the possible impact of multiple alert providers operating in the same systems, which may cause confusion [87].

The expectations of the system overall do not seem as optimistically biased, however, given that 60 to 70% of respondents reported they expected to receive false or missed alerts, across the three states. The respondents said that the system was still valuable, but held expectations of being told what happened as soon as possible, indicating that post-alert messages from the science agency (USGS) are important. Therefore, fast, clear information about the alerting types is critical to develop trust and understanding of the system in the three ShakeAlert states. Post-alert messaging [12] has been developed by the USGS and may play a vital role in the future to explain aspects of the system as well as develop trust and knowledge about earthquake early warning. However, if people do not know who to listen to regarding post-alert messaging, it could be problematic for developing knowledge and trust in the system.

Our findings regarding earthquake risk perceptions suggest that people do see themselves at risk from earthquakes, but do not see earthquakes as likely to have a substantial impact on their lives, and so may not expect earthquake early warning to be useful for them. Experience can inform expectations of earthquakes, so this finding is critical to understanding what people expect from future earthquakes.

All these expectations may shift with time and experience or even lack of experience with earthquakes and with the system. At issue is that OR and WA do not experience earthquakes as frequently as CA; it may be several years before these states receive any alerts [26]. Should this be the case, public education and earthquake drills could be utilized to inform people about the system and habituate them to the actions they can realistically take when they get an alert as well as to inform them when and why false or missed alerts may occur.

These findings represent more than the knowledge-behavior gap that has long been identified in disaster preparedness literature. Rather, there are gaps in understanding and expectations between both groups: the scientists and operators who manage the ShakeAlert system and the publics they seek to serve. Both have perceptions and goals for the system; however, these do not always align. We argue that for goals and expectations to be aligned both parties could extend their expectations to consider and align better with those of the other group. For example, operators could consider reducing alerting thresholds for interested publics, in recognition of their interests and the potential reassurance that an alert for even mild shaking might provide, and public educational efforts could target better understanding of why alerting thresholds might be higher, thus encouraging publics to expect higher alerting thresholds.

[8] The statewide ShakeAlert system was not yet operational at the time of the Ridgecrest earthquake sequence in 2019. While an app was available for Los Angeles County (only), it did not alert due to the ShakeAlert system determining that neither earthquake met the alerting thresholds for the county.

5.4. Global EEW development

Although these specific findings are limited to ShakeAlert on the US West Coast, they have broader relevance for the development of EEW globally. Public alerting is rapidly reaching hundreds of millions of people, mainly via a Google system that uses Android smartphone accelerometers as an ad hoc crowdsourced seismic network [88,89]. Private EEW systems may not have the same legal and social contracts as those managed as public systems. Understanding how early warning systems work, and how the social and technical elements of such systems interact and evolve over time should enable them to improve more rapidly. In principle, ongoing evaluation, feedback, and adjustment could be built into early warning systems from the outset. In practice, iterative, integrated socio-technical evaluation and improvement cycles (i.e., virtuous feedback cycles) for early warning systems are in their infancy, often relying on one-off case studies (e.g., [90]). Our study represents a first step toward longitudinal assessment of the operation and effects of EEW on the US West Coast, which may be useful for both private and public systems in the US and other nations to consider going forward.

5.5. Limitations

Our study is not without limitations, one of which is timing. Ideally a baseline survey like this would have been administered pre-CA rollout in October 2019, to capture that state's experience before alerts were sent. Due to the pandemic, rollouts were delayed in WA and OR until spring 2021, creating a discordant experience for people across the three states. However, one of the values this study may provide is that it suggests the differences of knowledge and understanding about ShakeAlert from the two states that had not rolled out at the time of the survey compared to one state that had. This creates an interesting dynamic in our study, where we can compare the influence of public rollouts versus pre-rollout perceptions and attitudes. Other limitations include those facing much survey research, such as potential sampling biases and insufficient representation of socially marginalized populations.

6. Conclusions and future research

This study was designed to increase understanding of perceptions, knowledge, and attitude of publics in WA, OR, and CA, the three states where ShakeAlert-powered alerts are now available statewide to be delivered to people and automated systems. Overall, we note that our respondents had a high level of false and missed alert tolerance, with some desiring to be alerted for any shaking they might feel. This expectation of the system does not necessarily match the expectations for alerting that scientists, emergency managers, and operators who manage the system may have (e.g., [91]). Where there are mixed expectation such as this, there is the possibility of public disappointment and reduced trust in the system. It may be beneficial for decision makers of the system to consider making alerts even lower than MMI III on an opt in basis (e.g. smartphone apps), at least while the system is still emerging and alerts are still rare. Especially in areas where MMI IV + earthquakes are rare, alerting for smaller earthquakes that might be felt has the potential to remind people that there are earthquakes and increase confidence in earthquake early warning. Over time and with more exposure to earthquakes, as in the cases of Japan and New Zealand, one could expect interest in lower alerting thresholds to decline.

Our research captures potential limitations in ShakeAlert's public education program as reflected by the misconceptions or lack of awareness respondents express. The relative newness of the system may explain some of these challenges to reaching and informing the public. To date, most public education programs have been focused on rollouts of ShakeAlert or linked to other initiatives like ShakeOut [59]. However, comprehensive campaigns are now beginning in museums and free choice learning environments, exploring other venues for public education [92]. Further, Did You Feel It? community intensity surveys are being developed to collect self-reported reactions and responses to EEW [34,93], which may provide additional insights. Exploring more pathways of public education and information will be important in shifting knowledge, awareness, and attitudes towards EEW and ShakeAlert in the future.

Repeating this survey and analysis regularly for the ShakeAlert states could illuminate trends in experiences, expectations, and preferences over time, as the system matures and evolves. International comparative analyses of earthquake and earthquake early warning experiences and expectations across New Zealand, Japan, Peru, and US studies (e.g., [16,19,94]), among others, could also be informative for ShakeAlert development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government. ShakeAlert® is a registered trademark of the US Geological Survey (USGS) and is used with permission. The survey described in this article was organized and implemented by the lead author at the University of Washington and was not conducted on behalf of the USGS. We thank our USGS internal reviewers, Dr. Emily Wilkins, and our Social Science Working Group collaborators for their insights, which greatly improved the survey development and the findings presented in this article. We also thank the three external reviewers for their contributions to this work. Funding was provided for this research through NSF Awards 1635593, 1948572, and 210371; all errors are the responsibility of the authors alone.

APPENDIX 1

The survey described in this article [75] was organized and implemented by the lead author at the University of Washington through NORC AmeriSpeak and was not conducted on behalf of the U.S. Geological Survey (USGS). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Many of the items in the survey reported on here reflect questions used in the TriNet Seismic Computerized Alert Network (SCAN) survey from the Trinet social science studies conducted in the late 1990's [71–73,95], which set the stage for later social science and interdisciplinary research on earthquake early warning (e.g., Ref. [1]. These studies were part of a larger project on Tri-Net network development, funded by USGS, Caltech, and the California (CA) Geological Survey to explore the potential for real-time earthquake early warning in CA as well as the policy and planning issues potentially involved in such a system. The Task 1 survey [72,95] and Task 2 report [73] (see also [71] directly influenced the development of the survey reported in Dunn et al. [1]; which was in turn adapted for the ShakeAlert baseline survey [75]. Both the TriNet studies and Dunn et al. [1] included focused, in-depth individual or group interviews to provide qualitative insights for survey instrument content. The TriNet SCAN survey included items to assess the following: who needs and has a right to alerting information; who should pay for the system; liability issues; the importance of differentiating between automated and human-mediated systems; comparative costs and benefits of early warning versus other mitigation and preparedness activities; the importance of comparing the consequences of acting versus not acting on warnings; the role of the media in early warning system development and implementation; and prioritizing among outcomes, such as life safety versus information system functioning. Specific items included in the TriNet SCAN survey addressed what might be done with different amounts of advance warning (10, 30, and 50 s); the current alert system; estimates of injuries, deaths and losses; willingness to pay for the EEW System; and exposure to media about earthquake early warning. While the objectives of the TriNet SCAN survey were focused on organizational users, the approach and findings are generally relevant for assessing EEW Systems for other users.

APPENDIX 2

The survey described in this article was organized and implemented by University of Washington through NORC AmeriSpeak and was not conducted on behalf of the US Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Appendix 2.1Additional details on weighting

A general population sample of adults age 18+ who reside in California, Oregon, and Washington was selected from the AmeriSpeak Panel for this study. Funded and operated by NORC at the University of Chicago, **AmeriSpeak®** is a probability-based panel designed to be representative of the US household population. Randomly selected US households are sampled using area probability and address-based sampling, with a known, non-zero probability of selection from the NORC National Sample Frame. These sampled households are then contacted by US mail, telephone, and field interviewers (face to face). The panel provides sample coverage of approximately 97% of the US household population. Those excluded from the sample include people with P.O. Box only addresses, some addresses not listed in the USPS Delivery Sequence File, and some newly constructed dwellings. While most AmeriSpeak households participate in surveys by web, non-internet households can participate in AmeriSpeak surveys by telephone. Households without conventional internet access but having web access via smartphones are allowed to participate in AmeriSpeak surveys by web. AmeriSpeak panelists participate in NORC studies or studies conducted by NORC on behalf of governmental agencies, academic researchers, and media and commercial organizations.

For more information, visit AmeriSpeak.norc.org.

The sample for this study was selected from the AmeriSpeak Panel using sampling strata based on age, race/Hispanic ethnicity, education, and gender (48 sampling strata in total). The size of the selected sample per sampling stratum was determined by the population distribution for each stratum. In addition, sample selection took into account expected differential survey completion rates by demographic groups so that the set of panel members with a completed interview for the study was a representative sample of the target population. If a panel household had one more than one active adult panel member, only one adult in the household was eligible for selection (random within-household sampling). NORC reported that calculating the weights for the AmeriSpeak Panel interviews involved the following sequential steps: incorporating the appropriate probability of selection, and then incorporating nonresponse and raking ratio adjustments (to population benchmarks).

For the AmeriSpeak Panel interviews, study-specific base weights were derived from the final panel weight and the probability of selection from the panel under the study sample design. Since not all sampled panel members responded to the interview, an adjustment was needed to compensate for survey non-respondents. This adjustment decreases potential nonresponse bias associated with sampled panel members who did not respond to the interview for the study. A weighting class approach was used to adjust the weights for survey respondents to represent non-respondents. At this stage of weighting, any extreme weights were trimmed using a power transformation to minimize the mean squared error, and then, weights were re-raked to the same population totals.

*Appendix 2.2 Sample demographics**

	California (N = 1219)	Oregon (N = 1020)	Washington (N = 1037)
GENDER			
Woman	52.2	50.4	49.7
Man	45.1	45.8	47.9
Transgender woman	0.9	0.2	0.3
Transgender man	0.1	0.9	0.7
Gender variant/non-conforming	0.2	1.8	0.6
Prefer not to answer	1.5	1	0.9
COMBINED RACE/ETHNICITY			
White, non-Hispanic	44.9	78.8	71.8
Black, non-Hispanic	5.9	1	2.1
Other, non-Hispanic	1.5	1.5	2.1
Hispanic	31.7	11.3	9.5
2+, non-Hispanic	2.5	5	6
Asian, non-Hispanic	13.5	2.4	8.6
EDUCATION			
Less than HS	6.9	7.8	6.8
HS graduate or equivalent	22.7	25	25.9
Vocational/tech school/some college/associates	30.8	29.5	31.9
Bachelor's degree	22.8	24	22.6
Post grad study/professional degree	16.7	13.7	12.8
AGE			
18–29	14.8	20.5	20.2
30–44	29.9	25.8	26.6
45–59	25.2	22.2	25.4
60+	30.2	31.5	27.8
HOUSEHOLD INCOME			
Less than $30,000	25.7	33.6	29.5
$30,000 to under $60,000	21.1	27	25.6
$60,000 to under $100,000	24.2	22	24.3
$100,000 or more	29	17.4	20.6
TYPE OF BUILDING OF RESIDENCE			
A one-family house detached from any other house	61.1	60.2	63.1
A one-family house attached to one or more houses	9.2	6.3	5.6
A building with 2 or more apartments	26.4	24.4	23.4
A mobile home or trailer	3	6.7	6.2
Boat, RV, van, etc	0.4	2.5	1.7

*Survey responses are weighted to represent individual state-level general adult population. The percentages in this table represent the weighted data.

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