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Alarm Technologies to Wake Sleeping People Who are Deaf or Hard of Hearing

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Abstract. Traditional fire alarms emit a high-frequency sound to alert the occupants of an imminent threat, which may be less appropriate for people who are deaf or hard of hearing. To address this issue, the scientific literature concerning alternative alarm technologies has been reviewed to evaluate their effectiveness in awakening people who are deaf or hard of hearing. The results show that low-frequency alarms, bed shakers and/or pillow shakers seem to be the most reliable existing technologies for this group of people. The main codes and standards relevant to these technologies have also been screened. This highlighted that a new standard for alarm technologies incorporating tactile signals might be needed. In addition, this paper presents the responses of 36 people who were deaf or hard of hearing participating to a survey in which their experiences and preferences in relation to fire alarm technologies were investigated. While some technologies have been identified in the literature as potentially effective, the survey responses indicate that people who are deaf or hard of hearing do not necessarily use them.

Keywords: Fire alarm, Hearing impairments, Deaf, Smoke alarm, People with disabilities, Functional limitations, Fire safety, Sleeping people, Evacuation, Egress

1. Introduction

Fire alarms play a key role during a fire emergency as they allow to timely act upon a fire threat [1]. In fact, the time needed by occupants before a purposive movement towards safety (often called pre-evacuation or pre-movement time [2]) can have a strong impact on safety, especially in buildings with a relatively small occupant load [3]. This leads to the need for reliable ways to both detect the fire as well as alert people exposed to such threat. This issue becomes particularly challenging in case of sleeping people since in the early stages of a fire, people take action upon interpreting fire cues [4]. In this context, fire alarms is one of the most important and affordable fire safety solutions adopted in buildings [5]. The alarm devices typically consists of two mechanisms; the detection mechanism that detects signs from the fire (typically smoke, heat or light [6]) and the warning

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mechanisms which warns the occupants of the imminent threat. The warning mechanism typically consists of an audio signal of high frequency [7].

Considering for example the US population, approximately 1% of people over the age of twelve experience hearing loss classified as severe (> 60 through 80 dBA) or profound (> 80 dBA), and more than 14% of the US population over the age of twelve experience hearing loss to some degree [8]. Hearing loss is also more prevalent in older age [9], and age related hearing loss (presbycusis) is estimated to affect approximately two thirds of Americans over the age of 70 [10], making it one of the most prevalent functional limitations among the elderly. As the population is ageing (United Nations, Department of Economic and Social Affairs, Population Division, [11]), the prevalence of hearing loss is likely to increase. An important deficit of commonly used audible alarms is its inability to warn people who are deaf and to some extent also people who are hard of hearing. This effect is further enhanced when people are asleep [12–14].

Based on these premises, it is necessary to explore which types of technologies are needed to wake sleeping people who are deaf or hard of hearing in case of emergency. One of the most popular alarm technologies for this purpose has been the use of visible signals, as mandated by NFPA 101 (National Fire Protection Association, [15]). However, evidence suggests that visible signals are ineffective in alerting people who are deaf or hard of hearing when asleep [12, 13, 16], 17, 14, 18]. For this reason, people with significant hearing loss may opt for using alternative devices offering other types of stimuli. This mainly includes devices offering tactile stimulus, such as bed shakers and pillow shakers. For people who are hard of hearing, low-frequency alarms has also been shown to be effective [12–14]. Nevertheless, several alternative technologies are available on the market and their suitability, reliability, potential applications and uses is still under investigation. In other words, several technologies available have not been scrutinized systematically. This issue occurs despite the critical role these devices may play in life safety for people with hearing loss. In addition, novel alarm technologies may not be standardized, thus potentially having on the market devices with heterogenous features. Recent advances in the domain of smart devices further justifies the need for more research in the field of alternative alarm technologies for people who are deaf or hard of hearing.

The aim of this work is therefore to obtain a better understanding on the available technologies for alerting people who are hard of hearing or deaf. This has been performed within a project initiated by the Fire Protection Research Foundation at the National Fire Protection Association (NFPA) and conducted by the Division of Fire Safety Engineering at Lund University [19]. This paper presents the key findings of this work, including a review of the currently available alarm and notification technologies for people who are deaf or hard of hearing in case of fire, based on their type of stimuli. The use of these technologies is also put in context by reviewing the main regulations, certification and approval processes for those devices. Additionally, the experiences and preferences of people who are deaf or hard of hearing were investigated through an online survey.

2. Methods

Given the overall aim of this work, three different methods have been adopted, namely (1) a scoping review of scientific literature, (2) a review of key codes and standards, (3) an online survey aimed at investigating the perspective of people who are deaf or hard of hearing.

2.1. A Scoping Review on Alarm Technologies

The PRISMA methodology has been used to perform the scoping review [20]. Five different databases (PsychInfo, PubMed, Scopus, Web of Science and NFPA Research Library & Archives) and one search engine (Google Scholar) were searched. To identify the literature, search strings were developed. The exact search strings for the different databases and search engine can be found in the full report associated with the project [19]. The reference lists of the reviewed publications were also screened for the identification of relevant additional records (e.g., the so-called "snowball" literature review approach).

As shown in Figure 1, the scientific literature was screened to identify the records to include according to the PRISMA methodology. This work involved removing duplicates from the multiple databases searched. Title and abstract were screened, and records deemed out of scope were excluded. The reasons for exclusion at this stage included research involving animals, dream research, and hearing loss evaluation studies. Records that could not be undoubtably determined to be irrelevant at this stage were assessed for eligibility by full-text screening at the next stage. Inclusion criteria were related to the testing of specific alarm technologies or other means to assess their performance. In phase two, the reasons for exclusion are given in Figure 1.

Relevant information to be included in the qualitative synthesis were then identified and compiled in an ad hoc reporting template developed for this purpose (see Table 1). The goal in this work was to obtain a comprehensive understanding on the effectiveness of the identified technologies. For this reason, the reporting template addressed aspects related to the technologies employed to awaken people who are hard of hearing or deaf and the effectiveness of these technologies to awaken people who are hard of hearing or deaf. In addition, negative effects on other populations from the use of the technology were screened along with codes and standards related to the technologies.

2.2. Review of Codes and Standards

The study included a review of codes and standards deemed relevant in the context of alarms for people who are deaf or hard of hearing. Codes and standards were included if they contained performance requirements related to any of the alarm technologies identified in the scoping review, or if they contained information on the application of such alarms. Performance requirements relate to the delivering the intended stimuli. Mentions of codes or standards were noted down during scoping of the literature. In addition, a search was conducted in nine major standards institutes to identify newer documents (institutes were mostly

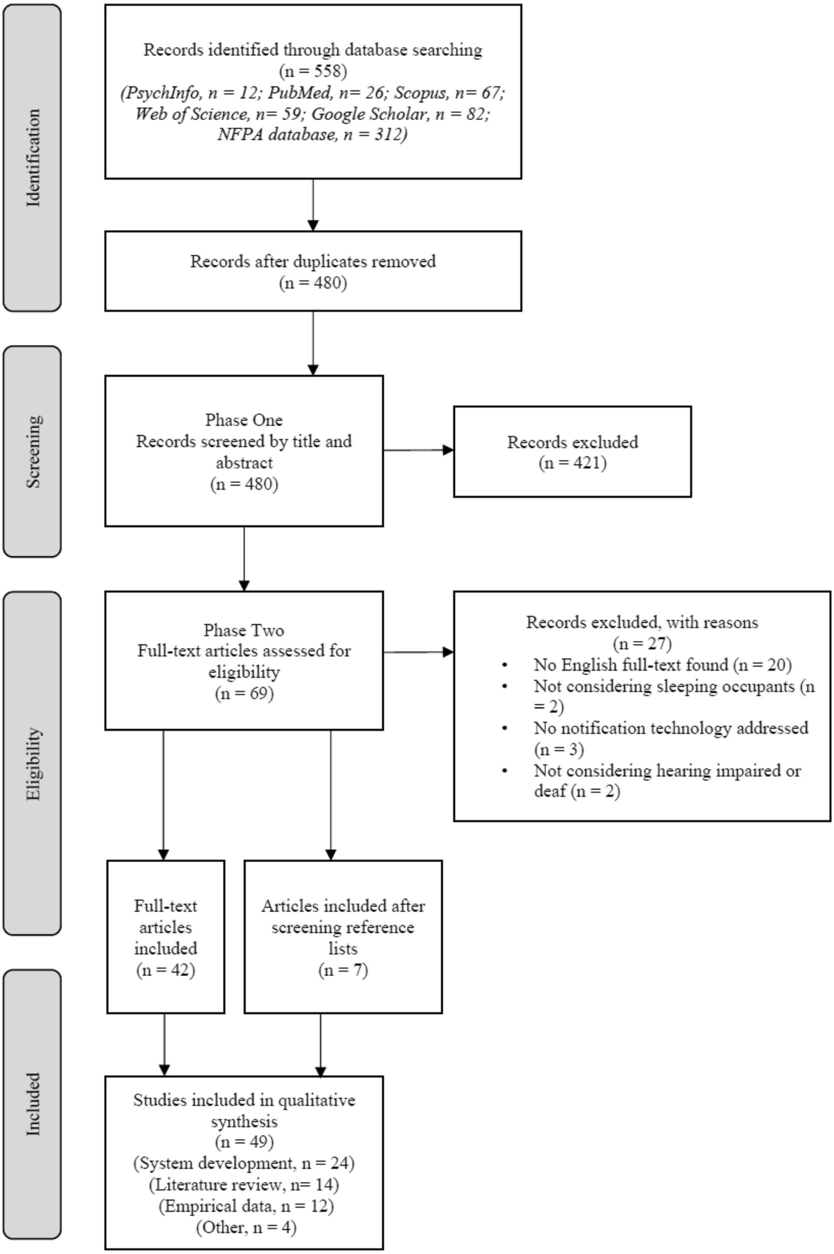

Figure 1. Flowchart of the scoping review adopted based on the PRISMA methodology. Note that some of the studies included in the qualitative synthesis were classified into more than one category, hence the mismatch in numbers in the bottommost box.

Table 1
Project Specific Standardized Reporting Table for the Identified Technologies

Technology
/Name of technology/
Primary stimulus afforded
/E.g. touch, vision, hearing, smell/
Description of the technology
/How it emits its stimuli. How it is powered. Where to place it. Portability. How it works. How it connects to the fire alarm/
How the technology is used today and its availability
/Is it used in other applications? Where is it available? How popular is it an alarm technology?/
Documented effectiveness for awakening people
/Scientific literature documenting the technology's effectiveness at waking people who are deaf or hard of hearing/
Possible or documented undesirable consequences for other parts of the population
/If it is known, documented issues with the technology for other parts of the population is presented. A reflection about possible undesirable consequences are also included./

suggested by the technical panel involved in the project but also included based on the expertise of the authors and the technical panel of the project). Codes and standards were sourced from: British Standards (BS), International standardization Organization (ISO), UL Standards, FM approvals, NFPA codes, Standards Australia, European Standards, International Code Council, and American National Standards Institute (ANSI). Codes and standards were then reviewed based on relevant information regarding requirements or specifications for the notification signal according to an ad hoc template, as shown in Table 2.

2.3. Online Survey with People Who are Deaf or Heard of Hearing

The experiences and preferences of people who are deaf or hard of hearing in relation to different alarm technologies were investigate through an online survey. The survey was explorative in nature, thus it was not aiming at identifying defini-

Table 2
Reporting Table for the Identified Codes and Standards

Type	/code or standard/
Name	/e.g. ISO XX "Standards for fire alarms"/
Edition	/e.g. First edition, January 2021. The date refers to the publication date/
First issued	/e.g. 2001/
Region	/e.g. International/
Scope	/a description of the scope of the code or standard/
Notification technology requirements	/a description of the code or standard and how it is relevant in terms of notification/

tive conclusions on the topic but rather provide insights into aspects that could not be identified with the literature review. Additionally, no attempt was made to differentiate between people who are deaf or hard of hearing considering that hearing abilities are here assumed as a continuous scale, and a valid categorization can only be accomplished through a diagnostic test.

The survey was developed after the initial list of available alarm technologies had been identified through the scoping review. This allowed to ask specifically about those technologies. The survey was divided into four different parts, including (1) Residence, (2) Experiences of different alarm technologies, (3) Preferences regarding alarm technologies in their primary residence, (4) Preferences regarding alarm technologies when visiting hotel or lodging establishment. Five-point Likert-scale questions were used to investigate the preferences of people. The complete survey questions can be found in the project report associated with this paper [19].

The results of the survey were then analysed by means of descriptive statistics. The survey was distributed through members of the Disabilities Access Review and Advisory Committee (DARAC) to organizations and people that might be interested to participate. In particular, the survey dissemination was facilitated by the technical panel of the project under which this study was conducted. This included consultants that were part of DARAC and members of the National Fire Protection Association (NFPA) with a specific effort to reach people who were deaf or hard of hearing. Since people facilitating the survey were all based in the US, survey respondents were from North America only. An invitation to participate in the survey was also posted on the NFPA website in an effort to increase the sample size.

3. Technologies to Wake Sleeping People

The scoping review resulted in 49 studies being included in the qualitative synthesis (see Figure 1), of which twelve contained relevant empirical data. From these twelve studies, thirteen technologies were identified. The technologies were categorized into four main types of stimuli, namely (1) Audible, (2) Olfactory, (3) Tactile and (4) Visual. Table 3 presents the technologies identified in the literature review, categorized by the primary stimulus they afford along with their characteristics and references to the studies presenting empirical data related to the technology. In addition, their current use/availability, expected effectiveness based on the scientific literature and undesirable consequences are presented. It should be noted that the findings are here presented in a qualitative fashion, and the readers are referred to the full report associated with this paper for more detailed information [19]. In addition, the information presented is sourced from the referenced studies. This means that undesirable consequences only refer to those presented (e.g. the readers should therefore consider the state-of-the-art of technologies/research at the time of publication).

Table 3
Summary of Identified Alarm Technologies for People Who are Deaf or Hard of Hearing

Technology	Primary stimulus afforded	Description	Current use and availability	Effectiveness (references)	Undesirable consequences
High-frequency alarm	Audible	Makes use of a high-frequency sound (> 2000 Hz) generally incorporated in smoke detection device	Widely used	Not effective for deaf people, limited effectiveness for people with hearing loss [12–14]	People on autism spectrum may get disoriented
Low-frequency alarm	Audible	Makes use of a low-frequency sound (around 520 Hz) generally incorporated in smoke detection device	Available in integrated or standalone devices	Effective for people with hearing loss, very limited effectiveness for deaf people [12–14]	Not found
Olfactory alarm	Olfactory	Spray device with different fragrances	Sparsely used as alarm clock, not found as emergency alarm	Limited effectiveness, dependent on the specific odour used [26–29]	Might be less suitable for people with allergy and/or asthma
Air movement	Tactile	Fans or similar aimed towards the sleeping person	Not found	Effective. Possibly less effective for children. Research is limited [30]	Not identified
Bed shaker	Tactile	Vibrating device installed under the mattress. Often connects to the fire alarm via sound recognition	Widely used in the deaf and hard of hearing community	Effective. Maybe less effective for older people [12, 14, 30–32]	Not identified
Electric shocks	Tactile	Electric shocks delivered via electrodes attached to the skin	Not found	Research is limited [33]	Not identified
Hearing-dog robot	Tactile	Robotic device that listens to the fire alarm and seeks up the person and 'nudges' him/her	One-off design	Research is limited. [34, 35]	Not identified
Heater	Tactile	Radiative heating device installed by the bed	Not found	Limited effectiveness, but research is also limited [28]	Potential fire hazard
Pager	Tactile	Small portable device that vibrates when activated	Widely used, but not for emergency alarm purposes and awakening	Research is limited [32]	Not identified

Table 3
Continued

Technology	Primary stimulus afforded	Description	Current use and availability	Effectiveness (references)	Undesirable consequences
Phone under pillow	Tactile	Regular cell phone installed under the pillow. Vibrates when activated and functions as a pillow shaker	Widely used, but not for emergency alarm purposes and awakening	Research is limited [34]	Potential fire hazard
Pillow shaker	Tactile	Vibrating device installed under the mattress. Often connects to the fire alarm via sound recognition	Widely used in the deaf and hard of hearing community	Effective. Maybe less effective for older people [12–14]	Not identified
Vibrating wristband	Tactile	Wearable device that vibrates when activated. Could listen to the fire alarm	Widely used, but not for emergency alarm purposes and awakening	Research is limited [32, 34]	Some might find it uncomfortable to sleep with such a device and might therefore take it off
Strobe light	Visual	Lights that are activated by the fire alarm and flashes. Often hardwired to the fire alarm system	Widely used	Limited effectiveness, but very dependent on installation distance from the occupant [12, 13, 16, 17, 14, 18, 30]	Depending on the flashing frequency, it could cause epileptic seizures or disorientation

4. Review of Key Codes and Standards Relevant to Alarm Technologies

Codes and standards concerning devices for waking up people that are deaf or hard of hearing were reviewed. A total of 19 codes or standards were identified. Table 4 presents the codes and standards identified and deemed relevant in this study. This includes the specific type of technology that is addressed in the code.

Only information deemed relevant has been extracted from the standards. This includes information related to the notification technology. For the purpose of this study, the latest published version of the identified standard or code were included in the review. Hence, no consideration was made to whether testing facilities are currently testing against the latest standard (the one included in this review) or against a previous version of the standard.

A summary of the scope and key notification technology requirements identified in each code/standard is here presented. This is based on the template adopted for the review, as discussed in the methods section.

Table 4
Identified Codes and Standards, as Well as Which Technology they Address

Code/Standard name	Technologies addressed
ANSI/ASA S3.41–2015 "Audible Emergency Evacuation (E2) and Evacuation Signals with Relocation Instructions (ESRI)" (American National Standards [36]	High-frequency alarm Low-frequency alarm
AS 1603.17:2020 "Automatic Fire Detection And Alarm Systems Warning Equipment For People With Hearing Impairment" (Standards [37])	High-frequency alarm Low-frequency alarm Bed shaker Pillow shaker Strobe light
AS 3786:2014 "Smoke alarms using scattered light, transmitted light or ionization" (Standards [38])	High-frequency alarm Low-frequency alarm
BS 5446–3:2015 "Detection and alarm devices for dwellings. Specifications for fire alarm and carbon monoxide alarm systems for deaf and hard of hearing people" [39]	Bed shaker Pillow shaker
EN 14,604:2005 "Smoke alarm devices" [40]	High-frequency alarm
EN 54–23:2010 "Fire detection and fire alarm systems—Part 23: Fire alarm devices—Visual alarm devices" [41]	Strobe light
EN 54–3:2014 + A1:2019 "Fire detection and fire alarm systems—Part 3: Fire alarm devices—Sounders" [42]	High-frequency alarm Low-frequency alarm
FM 3150 "Audible Notification Appliances for Automatic Fire Alarm Signaling" (FM [43]	High-frequency alarm
FM 3155 "Public Mode Visible Signaling Appliances for Automatic Fire Alarm Signaling" (FM [44])	Strobe light
International Building Code (IBC) (International Code Council, [45])	High-frequency alarm Low-frequency alarm Strobe light
ISO 8201:2017 "Alarm systems—Audible emergency evacuation signal—Requirements" [46]	High-frequency alarm Low-frequency alarm Bed shaker Pillow shaker Strobe light
NFPA 101 "Life Safety Code" (National Fire Protection Association, [15])	High-frequency alarm Low-frequency alarm Strobe light

Table 4
Continued

Code/Standard name	Technologies addressed
NFPA 72 "National fire alarm and signaling code" (National Fire Protection Association, [47])	High-frequency alarm Low-frequency alarm Bed shaker Pillow shaker Strobe light
UL 1638/CAN/ULC-S526 "Standards for safety—Visible signaling devices for Fire Alarm and Signaling Systems, Including accessories" (Underwriters [48])	Strobe light
UL 1971 "Standards for safety—Signaling devices for the hearing impaired" (Underwriters [25])	Bed shaker Pillow shaker Air movement Strobe Light
UL 217 "Standards for safety—Smoke alarms" (Underwriters [49])	High-frequency alarm Low-frequency alarm
UL 268/ULC-S529 "Smoke detectors for fire alarm systems" (Underwriters [50])	High-frequency alarm Low-frequency alarm
UL 464/ULC-S525 "Standards for safety—Audible Signaling Devices for Fire Alarm and Signaling Systems, Including Accessories" (Underwriters [51])	High-frequency alarm Low-frequency alarm
ULC-S531 "Standard for smoke alarms" (Underwriters [52])	High-frequency alarm Low-frequency alarm

ANSI/ASA S3.41-2015 is a standard specifying the characteristics of acoustics signals used for emergency evacuation. The standard specifies that the audible signal should consist of a "three-pulse" temporal pattern, similar to the pattern presented in ISO 8201:2017. The sound pressure level should comply with NFPA 72. For low-frequency alarms, the signal format shall be as specified in UL 464-2014. Mid frequency alarm signals are specified to produce frequencies ranging between 1000 Hz and 4000 Hz.

AS 1603.17:2020 is a standard specifying requirements for warning equipment aimed towards the hard of hearing population, and in particular to awaken members of that population. The standard specifies that such a device should be suitable for placement under the pillow, with no explicit mention of under the mattress installation. There is no explicit mentioning of the magnitude of vibration that needs to be fulfilled.

AS 3786:2014 is a standard containing specifications regarding test methods, functional criteria, and requirements for smoke alarms that uses scattered light, transmitted light or ionization. It covers smoke alarms that are intended for household applications or similar. When the alarm is activated, the sound pressure level needs to be less than 45 dBA, and then rising to the intended sound pressure level that should be lower than 105 dBA. An option of providing alarms with a fundamental frequency of 520 Hz is provided. An option to incorporate a voice message in the alarm is provided. In the standard, a test is specified with an aim to show that the smoke alarm is able to provide an 85 dBA sound pressure level (no more than 105 dBA) at 3 m distance.

BS 5446-3:2015 is a standard specifying requirements for fire and/or carbon monoxide alarm systems for people who are deaf and hard of hearing in dwellings. The standard defines a low frequency sounder as an audible device with a frequency in the range of 500 Hz to 1000 Hz. A vibrating device aimed towards waking up a person who is deaf or hard of hearing is referred to as a vibrating pad. The vibrating pad could be installed underneath a mattress or pillow. The standard also contains specification for visual alarm devices. Visual alarms are specified to emit either white or red light. Vibrating pads are specified to vibrate with a frequency within the range of 25–150 Hz. The vibrating pattern is specified to be pulsating with an active period of 2 ± 1 s followed by an inactive period of 2 ± 1.5 s. The peak-to-peak acceleration needs to be more than 4 g in the direction perpendicular to the primary usage plane while loaded with 100 g, and at least 15% of that acceleration in the direction perpendicular to the aforementioned. In each inactive period, the acceleration needs to be less than 15% of the maximum acceleration during the active period, for at least 1 s. Low frequency sounders intended for bedroom use should produce a sound pressure level of at least 75 dBA at 1 m distance, but no more than 110 dBA. Regarding provision of information, it is specified that a low frequency sounder is most effective at awakening when used in combination with a vibrating pad.

EN 14604:2005 is a standard applying to smoke alarms intended for household or similar residential application. For battery-powered and mains-powered alarms, it states that the sound output shall be 85–110 dBA, measured at 3 m from the appliance. The maximum nominal frequency shall not exceed 3500 Hz.

EN 54-23:2010 specifies requirements, test methods and performance criteria for fixed installation visual alarm devices. The visual alarm device shall produce white or red light. The flashing frequency shall be between 0.5 Hz and 2 Hz. There is an option for manufacturers to include synchronization possibilities to minimize adverse effects. The standard does not specify strict limits of luminosity. However, the visual alarm device needs to pass a test showing that the luminosity is greater than 1 cd for 70% of the measuring points, and never greater than 500 cd under the testing conditions specified.

EN 54-3:2014 + A1:2019 is a standard specifying requirements, test methods and performance criteria for fixed installation fire alarm sounders. It is stated in the standard that some European countries have specifications regarding the frequencies of sound and sound pattern. Therefore, the standard itself does not contain this information. However, for testing purposes the audible alarm is required to produce a sound pressure level of no less than 65 dBA in at least one direction.

FM 3150 is a standard containing performance requirements for electronically powered horns and bells for sounding alarms. The standard only contains performance criteria related to the audible characteristics in the form of minimum and maximum sound level. The minimum sound level is specified to be 75 dBA at minimum 3 m from the device, and maximum 120 dBA at the minimum hearing distance from the device. These requirements relate to public uses.

FM 3155 is a standard containing performance requirements for public mode visible signalling appliances for fire signalling. Examples of such systems includes high intensity strobes. The visible alarm appliances are specified to flash with a frequency of no more than 2 Hz and no less than 1 Hz. The colour should be clear or nominal white. The intensity shall not exceed 1000 cd. Additionally, the appliances should be subjected to the tests specified in chapter 27.1, and 27.4 in ANSI/UL 1971-2013.

The International Building Code (IBC) 2021 is a code including regulations related to fire safety. Chapter 9 of the code contains regulations related to fire alarms. It specifies that the sound pressure level should be 15 dBA over the average ambient sound level and 5 dBA over the maximum ambient sound level. The maximum sound level should be 110 dBA. Sleeping units in occupancies R-1 (transient residential) and R-2 (non-transient residential) shall be equipped with audible signalling appliances with a frequency of 520 Hz complying with NFPA 72. The 520 Hz signal is allowed to be produced by a separate listed notification appliance. Sleeping units in occupancies I-1 (custodial care facilities) and R-1 shall be equipped with visible alarm appliances.

ISO 8201:2017 is a standard specifying the requirements for audible alarm signals. The standard more specifically addresses two aspects of the audible signal: the temporal pattern and the sound pressure level. The temporal pattern specified is the "three-pulse" signal. The sound pressure level is specified to be at least 10 dBA over the background noise, and not less than 65 dBA. It is also specified that the above-mentioned signal pattern should be applied to tactile as well if they are used to supplement the audible signal when the background noise exceeds 110 dBA. Visual signals are specified to be operated at a frequency that considers the possibility of triggering epileptic seizures. No more guidance regarding this is provided.

NFPA 101 is a code providing minimum requirements for life safety in case of fire and other emergencies. The code contains different requirements depending on occupancy. A 520 Hz low-frequency alarm in compliance with NFPA 72 is required to be installed in sleeping rooms in the following occupancies: new hotels and dormitories, and new apartment buildings. Sleeping rooms shall be provided with a visual notification appliance in the following occupancies: new hotels and dormitories (in guest rooms and guest suites specifically required and equipped to accommodate hearing-impaired occupants), new and existing apartment buildings, and some lodging or rooming houses (not required where the proprietor resides in the building and there are five or fewer rooms for rent).

NFPA 72 is a code applying to fire alarm systems, supervisory station alarm systems, public emergency alarm reporting systems, fire and carbon monoxide detection and warning equipment, and emergency communication systems. According to the code, the sound pressure level of audible notification appliances shall not exceed 110 dBA at the minimum hearing distance. The evacuation signal should be synchronized within a notification zone. The audible signal shall be in the form of a temporal-three pattern. In sleeping areas, the sound pressure level of audible appliances should be at least 15 dBA above the average ambient sound level, 5 dBA above the maximum sound level, or at least 75 dBA, whichever is greatest. The sound level should be measured at the pillow. The audible appliance intended for awakening occupants should produce a low frequency alarm sound with a fundamental frequency of 520 Hz $\pm$ 10%. The low frequency audible appliance should also be listed to produce this frequency. For visual notification appliances, the flashing frequency shall be between 1–2 Hz. The colour shall be clear or nominal white and the effective intensity should not exceed 1000 cd. Depending on the mounting height, the effective intensity shall be at least 110 or 177 cd. The visual notification appliance shall be located within 4.9 m of the pillow. Tactile appliances are permitted if used in addition to audible and/or visual notification appliances. Notification appliances in sleeping rooms or guest rooms should consist of a low-frequency alarm as specified above, if the occupant has mild or severe hearing loss and if it is mandated by laws, codes or standards, or if it is provided voluntarily. For people with moderately severe to profound hearing loss, the notification appliance should be visual and tactile if it is mandated by laws, codes or standards, or if it is provided voluntarily.

UL 1638/CAN/ULC-S526 is a standard applying to visual signalling devices. Visible signals intended for emergency warning shall produce an intensity of 15–1000 cd and a flash rate of 1–2 Hz. The standard also specifies the dispersion of the visual signal. If there is more than one device producing the visual output, the signals should be synchronized.

UL 1971 is a standard covering the requirements of emergency-signalling devices for the hearing impaired, including strobes, vibrating alarms, and air-movement. For alarms producing light as output, the intensity is not specified. However, the dispersion and measurement of light intensity is specified. It is also specified that the frequency should be no less than 1 Hz and no greater than 2 Hz. If there are multiple light sources, they should be synchronized. Vibrating alarms should produce a radial displacement of 1/8 inch (3.2 mm) minimum. The frequency of the vibration should be between 60 Hz and 120 Hz and the device should have a cross-sectional area of at least six square inches for its biggest dimension. Air movement should produce a peak velocity of at least 270 ft./min (1.37 m/s), affecting a two-foot square area. The signal format should be from zero to peak velocity with 15–20 cycles per minute.

UL 217 is a standard covering the requirements of electrically operated single and interconnected multiple station smoke alarms intended for indoor use, as well as “travel” alarms. The smoke alarms covered by this standard is self-contained standalone alarms powered via either supply source or batteries. Smoke alarms that are intended for connection to a control unit is not covered by this standard, but by UL 268 instead. The pattern of the alarm signal is specified to be in the temporal-three pattern. The standard also permits the inclusion of a voice signal. The alarm should be able to produce an 85 dBA signal at 3.05 m distance for at least 4 min. Supplementary remote sounding appliances intended to be installed in bedrooms shall not produce a sound output lower than 85 dBA if not marked with appropriate text. The sound output should under no circumstances produce a sound output lower than 75 dBA. The standard also contains specifications for low frequency alarm signals. The fundamental frequency should be 520 Hz (± 10%) with various harmonic frequencies. The sound output at the harmonic frequencies should be at least 5 dBA lower than the fundamental frequency, and no less than 20–50 dBA lower than the fundamental frequency (depending on which harmonic). Revisions dated 28th of April 2021 contains updated requirements for sound pressure levels for low-frequency alarms. Low-frequency alarms are now allowed to produce a sound pressure level of 79 dBA instead of 85 dBA, which is the requirement for high-frequency alarms.

UL 268/ULC-S529 is a standard that in contrast to UL 217 covers smoke alarms that are part of a bigger fire alarm system. The pattern of the alarm signal is specified to be in the temporal three pattern. The standard also permits the inclusion of a voice signal. The alarm should be able to produce an 85 dBA signal at 3.05 m distance for at least 4 min. The standard also contains specifications for low frequency alarm signals. The fundamental frequency should be 520 Hz (± 10%) with various harmonic frequencies.

UL 464/ULC-S525 is a standard applying to audible signalling devices for fire alarm and signalling systems. The pattern of the alarm signal is specified to be in the temporal three pattern. The alarm should be able to produce an 85 dBA signal at 3.05 m distance for at least 4 min. For dwelling units in Canada, the device shall not produce a sound output lower than 85 dBA if not marked with appropriate text. The sound output should under no circumstances produce a sound output lower than 75 dBA. The standard also contains specifications for low frequency alarm signals. The fundamental frequency should be 520 Hz (± 10%) with various harmonic frequencies.

ULC-S531 is a standard covering the requirements for electrically operated single and interconnected multiple station smoke alarms intended for indoor use. The smoke alarms covered by this standard is self-contained standalone alarms powered via either supply source or batteries. The pattern of the alarm signal is specified to be in the temporal-three pattern. The standard also permits the inclusion of a voice signal. The alarm should be able to produce an 85 dBA signal at 3.05 m distance for at least 4 min. Supplementary remote sounding appliances intended to be installed in bedrooms shall not produce a sound output lower than 85 dBA if not marked with appropriate text. The sound output should under no circumstances produce a sound output lower than 75 dBA. The standard also contains specifications for low frequency alarm signals. The fundamental frequency should be 520 Hz (± 10%) with various harmonic frequencies.

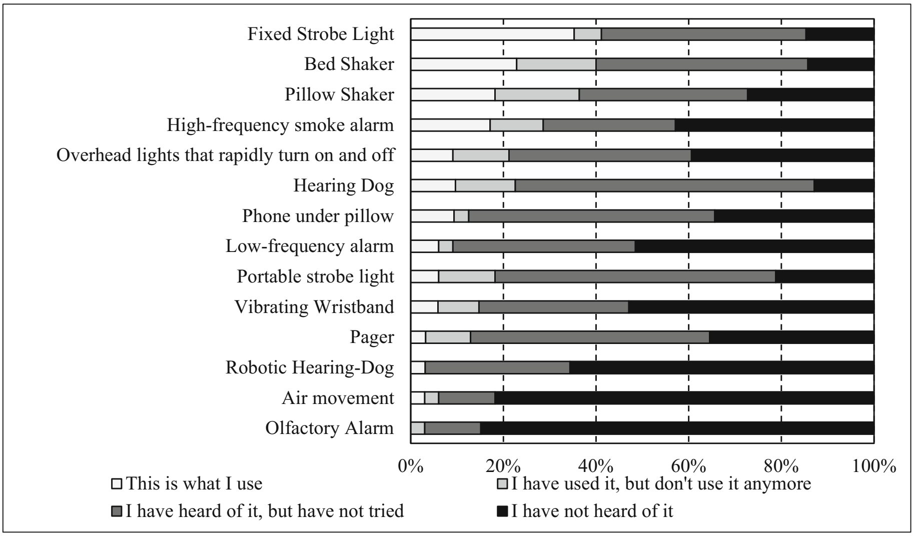

Figure 2. Experiences with different alarm technologies of people who were deaf or hard of hearing (N = 35).

In conclusion, the 19 identified codes and standards covered six of the thirteen technologies identified in the scoping review, namely: high-frequency alarm (n = 14), low-frequency alarm (n = 12), strobe light (n = 9), bed shaker (n = 5), pillow shaker (n = 5), and air movement (n = 1). Most codes and standards addressed high-frequency alarms. This is not surprising, being the most common alarm technology. Additionally, the requirements related to audible alarm were most consistent in specification and mode of measurement, while more variation were found relating to vibrating alarms.

5. Survey Results

In total, 36 people who were deaf or hard of hearing responded to the survey. Twenty-six of the respondents resided in the United States, and ten resided in Canada. Respondents were not obliged to answer all questions. Hence, the specific number of answers for each question are given in the figure captions. The key findings from the survey are presented here.

The survey respondents were asked regarding their experience with various alarm technologies. The alarm technologies identified in the scoping review of scientific literature, as well as some other technologies known by the authors and members of the technical panel were included. The survey responses displayed in Figure 2.

The survey respondents were also asked for their preference regarding various characteristics of fire alarm technologies, in the setting of their primary residence. The results are shown in Figure 3.

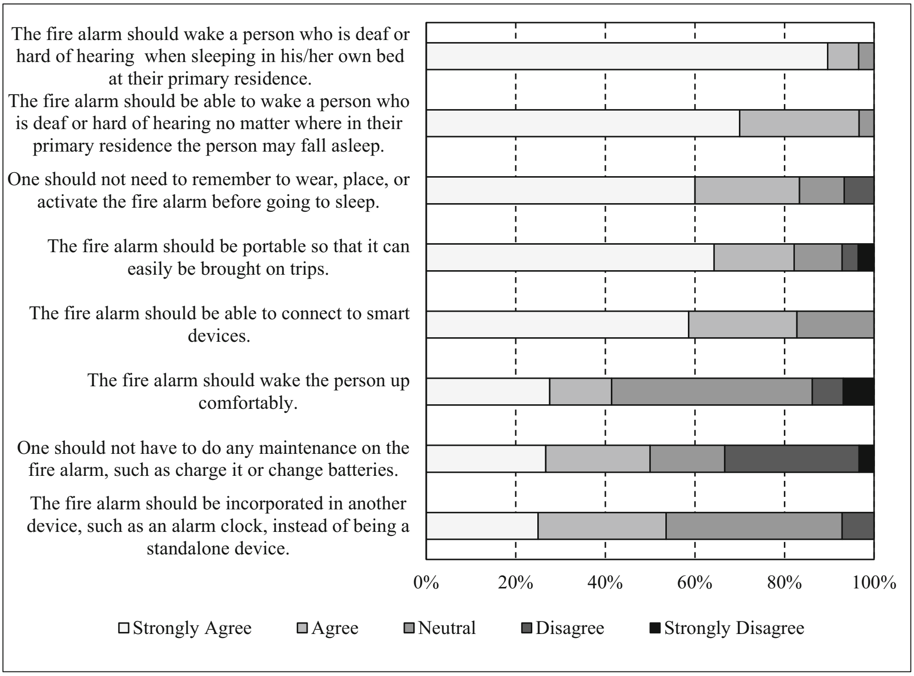

Figure 3. Preference of people who were deaf or hard of hearing when it comes to alarm characteristics in their primary residence (N = 30).

The survey respondents were also asked if they usually bring their own alarm technology, or if they relied on the hotel or lodging establishment to provide it to them, whenever visiting such accommodations. Results showed that 19 people declared they would rely on the hotel, two will bring their own and six they will bring their own but also rely on the hotel.

In addition to their preferences in the residential setting, the survey respondents were also asked about their preferences when visiting lodging or hotel establishments. These results are shown in Figure 4.

6. Discussion

This work shows that there is a variability in the extent to which different technologies have been investigated by the scientific community and manufacturers. The most investigated technologies include audible alarms (both high-frequency and low-frequency), strobe lights, and bed/pillow shakers. It should be noted that no effort was made to identify possible alarm technologies that are presently not applied in the context of awakening sleeping people who are deaf or hard of hearing. Also, the main aim was to investigate the technology producing a given stimuli for evacuation alarm in isolation rather than how various technologies could

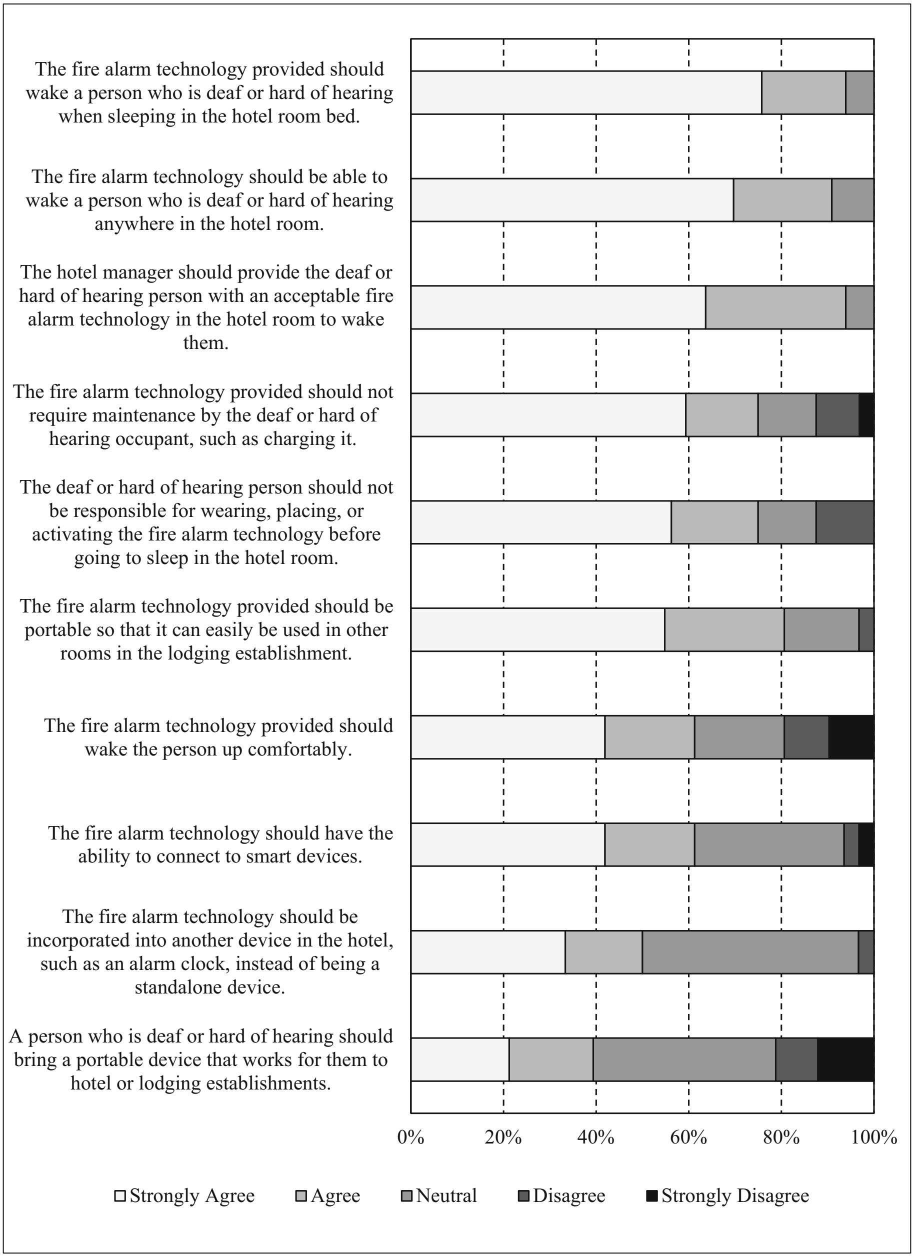

Figure 4. Preference of people who were deaf or hard of hearing when it comes to alarm characteristics when visiting hotel or lodging establishment (N = 33).

be combined for alarm applications. The review included only technologies that have been scientifically tested on people who are deaf or hard of hearing or on other populations if the primary stimulus addressed by the technology was not audible.

High frequency-smoke alarms are reported in the literature as an inefficient mean in awakening people who are deaf and hard of hearing [21]. The low-frequency smoke alarm is significantly more effective for people who are hard of hearing, but still ineffective for people who are deaf [12–14]. Strobe lights are today commonly used, but are deemed to be less effective at awakening people who are deaf or hard of hearing than what has previously been assumed [13, 16], 17, 14, 18. Bed shakers and pillow shakers have gained traction in recent years as an effective means for awakening people who are deaf or hard of hearing. However, effectiveness in older age group is limited and deserves further research [13]. A limiting factor is that there is currently no satisfactory standardized way of measuring the vibrational capabilities of these devices, to the best of the authors' knowledge. This has been recognized as a key issue by researchers in this field [13]. It is therefore argued that a standardized measurement would facilitate research into their effectiveness.

Much of the data concerning awakening of sleeping people who are deaf or hard of hearing are collected with fairly young populations. However, the sleeping patterns of a young and old individual are not the same [22], and people who are older may be more likely to awake due to the decrease in slow-wave sleep [23]. This is in contrast with the findings reported by Bruck and Thomas [13] regarding the effectiveness of bed shakers and pillow shakers. This issue deserves further research, as hearing loss is more prevalent in older populations [9].

Although many of the studies included in this review report thresholds for awakening, these numbers should be treated with caution. Previous research has shown that priming (i.e. altering the meaningfulness of the signal) increased the likelihood of waking up from 25% to 90% [24]. The thresholds might therefore be seen only as a mean to rank the effectiveness of different alarm technologies within a study.

Evidence suggests that people may be more or less sensitive to different kinds of stimuli [13]. This is also supported by the vast individual differences reported in the different studies. Nonetheless, technologies incorporating certain kinds of stimuli have been shown to be generally more effective for certain groups, such as low-frequency audible alarms for people with moderate hearing loss, and vibrating alarms for people with severe hearing loss or deaf. This provides evidence for recommending certain technologies to certain groups. Nevertheless, the functional limitations of an individual (possibly including more than one limitation) could be considered when assessing the effectiveness of a given technology for an individual.

One important future endeavor is to develop a new standard for bed and pillow shakers and other tactile alarm technologies. As of today (and as of 2007 based on [13]), there are only few standard available, e.g., BS 5446-3:2015 [39] and UL 1971, third edition [25] reporting vibrational requirements for bed and pillow shakers. For the latter standard, no details on how the vibrational strength should be measured could be sourced, other than it should have a radial displacement of at least 1/8 inch (3.2 mm). A useful standard should be placement-independent. In other words, it should be possible to use the standard for a variety of different vibration technologies. In this context, research on appropriate vibration levels needs to be conducted in a sleep laboratory including people who are deaf and hard of hearing. Such tests should be based on expertise in the fields of sleep research, audiology, and mechanical vibration in order to achieve the intended outcomes. It is therefore recommended that future empirical research on the effectiveness of bed shakers or pillow shakers make use of an informed standard test procedure to characterize intensities of different devices. However, the issue that the vibration from the device is transmitted differently to the user depending on the specific installation (i.e., under a mattress or under a pillow) remains unsolved. This should be made classifying the technologies according to their performance in providing the user with tactile feedback, rather than their vibrational capabilities in an artificial setting not resembling a realistic application. This will allow manufacturers to be more creative, and research into the subject would be facilitated.

The results from the survey provide valuable insight into the experiences and preferences of people who are deaf or hard of hearing in relation to alarm technologies. A limitation associated with these results is that the number of responses was limited, meaning that findings should be considered explorative rather than conclusive. Furthermore, the respondents resided in North America, thus results may need to be scrutinized prior applying them to other countries. Findings highlight that experience with various alarm technologies is quite limited, with fixed strobe lights, bed and pillow shakers, and high-frequency audible alarms being the most used technologies. This is in line with the provision of these alarms on the market. The low-frequency alarm seems to be largely unknown despite its proven efficiency. This might indicate that more efforts need to be done towards promoting this kind of alarm technology.

The preferences related to alarm technologies were similar irrespective of context (residence or hotel/lodging establishment). The most agreed upon important characteristic was, unsurprisingly, the technology's ability to wake a person. It was also considered important that the alarm should be able to wake up people no matter where they might fall asleep. In relation to occasional visits to hotels or lodging establishments, the respondents stated that they generally relied on the establishment to provide an alarm for them. Other aspects related to self-reliance (not having to wear the device or activate it) were also deemed important. However, having to maintain the alarm has been indicated as a minor issue. While considering these preferences, they seem to be fulfilled by a regular audible smoke alarm. These preferences can be addressed only by some of the available alternative alarm technologies. For example, a bed shaker seems to be an effective way of wakening people who are deaf or hard of hearing, but only so when installed in the location in which they are sleeping. This highlights that the experiences of the target group should be taken into account when identifying the most suitable technologies to be used for a given purpose.

7. Conclusion

The scoping review highlights that low-frequency audible alarms are effective for people who are hard of hearing and for older age groups, and that bed/pillow shakers could be effective for people who are hard of hearing or deaf. However, more research is needed regarding the effectiveness of bed/pillow shakers in relation to older age groups. It is also deemed necessary to re-evaluate the recommendation of strobes as an alternative alarm technology for awakening people who are deaf or hard of hearing. While some technologies have been identified in the literature as potentially effective (e.g., low-frequency audible alarms, bed/pillow shakers), the survey conducted indicates that people who are deaf or hard of hearing do not necessarily commonly use them. It is therefore argued that information campaigns may be needed towards this target group. It is also argued that efforts are aimed towards developing a usable standard for alarm technologies incorporating tactile signals.

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References

1. Lindell MK, Perry RW (2012) The protective action decision model: theoretical modifications and additional evidence. Risk Anal 32(4):616–632. https://doi.org/10.1111/j.1539-6924.2011.01647.x
2. Ronchi E (2020) Developing and validating evacuation models for fire safety engineering. Fire Saf J . https://doi.org/10.1016/j.firesaf.2020.103020
3. Purser DA, Bensilum M (2001) Quantification of behaviour for engineering design standards and escape time calculations. Saf Sci 38(2):157–182. https://doi.org/10.1016/S0925-7535(00)00066-7
4. Palmer DL (1999) Should bedroom doors be open or closed while people are sleeping?
5. Rohde D, Corcoran J, Sydes M, Higginson A (2016) The association between smoke alarm presence and injury and death rates: a systematic review and meta-analysis. Fire Saf J 81:58–63. https://doi.org/10.1016/j.firesaf.2016.01.008
6. Liu Z (2003) Review of recent developments in fire detection technologies. J Fire Prot Eng 13(2):129–151. https://doi.org/10.1177/1042391503013002003
7. Huey RW, Buckley DS, Lerner ND (1996) Audible performance of smoke alarm sounds. Int J Ind Ergon 18(1):61–69
8. Goman AM, Lin FR (2016) Prevalence of hearing loss by severity in the United States. Am J Public Health 106(10):1820–1822. https://doi.org/10.2105/AJPH.2016.303299
9. Lin FR, Niparko JK, Ferrucci L (2011) Hearing Loss Prevalence in the United States. Arch Intern Med 171(20):1851–1853. https://doi.org/10.1001/archinternmed.2011.506
10. Tu NC, Friedman RA (2018) Age-related hearing loss: unraveling the pieces. Laryngoscope Investigat Otolaryngol 3(2):68–72. https://doi.org/10.1002/lio2.134
11. United Nations, Department of Economic and Social Affairs, Population Division (2020) World Population Ageing 2019 (ST/ESA/SER.A/444; p 64)
12. Ashley EM (2007) Waking effectiveness of emergency alerting devices for the hearing able, hard of hearing, and deaf populations. University of Maryland
13. Bruck D, Thomas I (2007) Waking effectiveness of alarms (auditory, visual and tactile) for adults who are hard of hearing. Fire Protection Research Foundation
14. Du Bois J, Ashley E, Klassen M, Roby R (2005) Waking effectiveness of audible, visual and vibratory emergency alarms on people of all hearing abilities. Proceedings of the Accessible Emergency Notification and Communication: State of the Science Conference, Gallaudet University, Washington DC
15. National Fire Protection Association (2021) NFPA 101, Life Safety Code
16. Bowman SK, Jamieson DG, Ogilvie RD (1995) Waking effectiveness of visual alerting signals. J Rehabilitat Res Dev 32(1):43–54
17. Bryan V, Penney G, Andrew L, Russo MR (2014) Chapter 28—Empirical study using alternative early warning systems to address fire in homes of deaf or hard of hearing individuals. In: Handbook of research on Education and Technology in a Changing Society (Vol. 1–2). IGI Global
18. Bryan VC, Penney G, Russo MR, Dennett S (2013) Final report: early warning technology for eople with profound hearing loss (p. 61)
19. Smedberg E, Ronchi E (2021) Review of alarm technologies for deaf and hard of hearing populations (FPRF-2021-09). Fire Protection Research Foundation
20. Tricco C, Lillie A, Zarin E, O'Brien WK, Colquhoun K, Levac H, Moher D, Peters DJ, Horsley T, Weeks L, Hempel S, Akl EA, Chang C, McGowan J, Stewart L, Hartling l, Aldcroft A, Wilson M, Garritty C, Straus S (2018) PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Internal Med 169(6):467–473

21. Thomas I, Bruck D (2010) Awakening of sleeping people: a decade of research. Fire Technol 46(3):743–761. https://doi.org/10.1007/s10694-008-0065-5
22. Ohayon MM, Carskadon MA, Guilleminault C, Vitiello MV (2004) Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: developing normative sleep values across the human lifespan. Sleep 27(7):1255–1273. https://doi.org/10.1093/sleep/27.7.1255
23. Zepelin H, McDonald CS, Zammit GK (1984) Effects of age on auditory awakening thresholds. J Gerontol 39(3):294–300. https://doi.org/10.1093/geronj/39.3.294
24. Wilson WP, Zung WWK (1966) Attention, discrimination, and arousal during sleep. Arch Gen Psychiatry 15(5):523–528. https://doi.org/10.1001/archpsyc.1966.01730170075011
25. Underwriters Laboratories (2002) Standards for safety – Signaling devices for the hearing impaired, UL 1971 (Ed. 3)
26. Bruck D, Brennan P (2001) Recognition of Fire Cues During Sleep. [PhD Thesis]. Interscience Communications
27. Carskadon MA, Herz RS (2004) Minimal olfactory perception during sleep: why odor alarms will not work for humans. Sleep 27(3):402–405
28. Kahn MJ (1984) Human awakening and subsequent identification of fire-related cues. Fire Technol 20(1):20–26
29. Lynch J (1998) Nocturnal olfactory response to smoke odor. Human Behavior in Fire Proceedings of the 1st International Symposium, Belfast, Northern Ireland, 1998 231–242
30. UL (1991) Report of research on emergency signaling devices for use by the hearing inmpaired (Subject 1971). Underwriters Laboratories
31. Murphy T, Alloway C, LaMarche C, Bernstein D, Ogilvie R, MacLean A, Jamieson D (1995) How reliably does a vibro-tactile smoke alarm awaken individuals with hearing loss. Sleep Research A, 24
32. Roby R (2005) Phase SBIR I report: smoke detector alert for the deaf. Combustion Science and Engineering, Inc
33. Pisano M, Rosadini G, Rossi GF, Zattoni J (1966) Relations between threshold of arousal and electroencephalographic patterns during sleep in man. Physiol Behav 1(1):55–58
34. Sekiya D, Nakamura T, Kanoh M, Yamada K (2017) Can a robot wake a sleeping person up by giving him or her a nudge? Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, 279–280. https://doi.org/10.1145/3029798.3038349
35. Yoshida Y, Sekiya D, Nakamura T, Kanoh M, Yamada K (2018) Hearing-dog robot to wake people up using its bumping action. In: Lee R (Ed) Computational Science/Intelligence and Applied Informatics. Springer International Publishing. Vol. 726, pp 41–50. https://doi.org/10.1007/978-3-319-63618-4_4
36. American National Standards Institute (2015) Audible Emergency Evacuation (E2) and Evacuation Signals with Relocation Instructions (ESRI), ANSI/ASA S3.41–2015
37. Standards Australia (2020) Automatic fire detection and alarm systems warning equipment for people with hearing impairment, AS 1603.17:2020
38. Standards Australia (2014) Smoke alarms using scattered light, transmitted light or ionization, AS 3786:2014
39. British Standards Institution (2015) Detection and alarm devices for dwellings. Specifications for fire alarm and carbon monoxide alarm systems for deaf and hard of hearing people, BS 5446-3:2015
40. European Committee for Standardization (2008) Smoke alarm devices, EN 14604:2005

41. European Committee for Standardization. (2010). *Fire detection and fire alarm systems—Part 23: Fire alarm devices—Visual alarm devices, EN 54–23:2010*
42. European Committee for Standardization (2019) Fire detection and fire alarm systems—Part 3: Fire alarm devices – Sounders, EN 54–3:2014 + A1:2019
43. FM Approvals (2020a) Audible Notification Appliances for Automatic Fire Alarm Signaling, FM 3150
44. FM Approvals (2020b) Public Mode Visible Signaling Appliances for Automatic Fire Alarm Signaling, FM 3155
45. International Code Council (2021) International Building Code
46. International Organization for Standardization (2017) Alarm systems—Audible emergency evacuation signal—Requirements. ISO 8201:2017
47. National Fire Protection Association (2019) NFPA 72, National fire alarm and signaling code
48. Underwriters Laboratories (2016b) Standards for safety: Visible signaling devices for Fire Alarm and Signaling Systems, Including accessories, UL 1638 (Ed. 5) / CAN/ULC-S526 (Ed. 4)
49. Underwriters Laboratories (2020) Standards for safety—Smoke alarms, UL 217 (Ed. 9)
50. Underwriters Laboratories (2016a) Smoke detectors for fire alarm systems, UL 268 (Ed. 7) / ULC-S529 (Ed. 4)
51. Underwriters Laboratories (2016c) Standards for safety: Audible Signaling Devices for Fire Alarm and Signaling Systems, Including Accessories, UL 464 (Ed. 10) / ULC-S525 (Ed. 4)
52. Underwriters Laboratories (2019) Standard for smoke alarms, ULC-S531:2019 (Ed. 4)