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TECHNICAL NOTES

Review of Alarm Technologies for Deaf and Hard of Hearing Populations

Final Report by:

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Foreword

It is estimated that nearly 3 million Americans experience severe hearing loss and over 41 million Americans experience hearing loss to some degree. Audible and visible alarms are required in sleeping rooms, such as hotel rooms which may be occupied by people who are deaf or hearing impaired. However, evidence suggests that strobe lights are ineffective in alerting such people when asleep. A previous Research Foundation study also shows that older adults also may fail to respond to both audible and visible alarms. People with significant hearing loss compensate by using alternative devices such as bed shakers, portable devices that alert them of alarm activation by detecting the audible signal and vibrating in response. Despite the critical role these devices play in life safety for people with hearing loss, they are not standardized, and their effectiveness is not fully understood. This research study provides a review of the currently available alternative alarm and detection technologies and their respective characteristics, use cases, regulations and certification and approval processes for the deaf and hard of hearing community.

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Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: alarms, bed shakers, pillow shakers, strobe lights, low-frequency alarms, high-frequency alarms, deaf, hard of hearing

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Abstract: Fire alarms are used in order to inform occupants of an imminent fire threat and they have been shown to be effective in reducing the number of injuries and fatalities related to fires. The traditional fire alarm consists of a sounder emitting a high-frequency sound, which may be less appropriate for people who are deaf or hard of hearing. The aim of this research has been to investigate what available alternative alarm technologies exist and their documented effectiveness in awakening people who are deaf or hard of hearing. This document also includes both a review of codes and standards that these technologies may be subjected to, as well as a survey exploring the experiences and preferences of people who are deaf or hard of hearing, and other relevant stakeholders, in relation to fire alarm technologies. Based on the evidence identified in the review of existing technologies, low-frequency alarms, bed shakers and/or pillow shakers seem to be the most reliable technologies for this group of people, also considering the amount of evidence that exists in the scientific literature. The review has provided an overview of the main codes and standards that exist, and some of the relevant requirements contained within them. Based on this review, it is argued that efforts should be aimed towards developing a usable standard for alarm technologies incorporating tactile signals. While some technologies have been identified in the literature as potentially effective, the survey conducted indicates that people who are deaf or hard of hearing do not necessarily use them. The survey also indicates that support persons and fire safety experts may also recommend technologies that have been proven ineffective in the scientific literature. It is therefore argued that information campaigns are needed towards these target groups.

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1. Introduction

The possibility to be alarmed early on during a fire emergency is a key factor to timely act upon the threat [1]. In fact, the so-called pre-evacuation time (intended here as the time needed by occupants before a purposive movement towards safety [2]) can have a strong impact on safety, especially in buildings with a relatively small occupant load [3]. Considering the fire evacuation time-line [4], this means that we need a reliable way to detect the fire, and subsequently alert the occupants exposed to such threat. Typically, both these functions are incorporated in a smoke alarm, but they could also be afforded by different devices. The installation and use of smoke alarms is one of the most important fire safety solutions adopted in buildings (e.g., especially in residential settings). This can be seen in the effectiveness of smoke alarms to prevent residential fatal fires [5]. As stated, 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 mechanisms which warns the occupants of the imminent threat. Traditionally, the warning mechanism has consisted of an audio signal of high frequency [7], which has its limitation especially in relation to people with hearing loss.

It is estimated that almost 1 out of 100 US citizens over the age of twelve experience hearing loss classified as severe (>60 through 80 dBA) or profound (>80 dBA) hearing loss, and more than 14 out of 100 US citizens over the age of twelve experience hearing loss to some degree [8]. Hearing loss is also more prevalent in older age [9]. As the population is ageing [10], 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 [11]–[13]. This issue is even further emphasized when considering that people tend to underestimate fire risk [14], and in general do not respond well to the stimuli produced by the fire itself during sleep [15].

Based on these premises, it appears evident that 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 [16]. However, evidence suggests that visible signals are ineffective in alerting people who are deaf or hard of hearing when asleep [11]–[13], [17]–[19]. For this reason, people with significant hearing loss may opt for using alternative devices offering other types of stimulus. 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 [11]–[13]. Nevertheless, several alternative approaches are available on the market and it is still unclear their suitability, reliability, potential applications and uses in current and future buildings. This means that there are several technologies available that have not been scrutinized systematically. This happens despite the critical role these devices may play in life safety for people with hearing loss. It should also be noted that some of them may not be standardized, and their effectiveness is not fully understood. Recent advances in the domain of smart devices (e.g., in residential settings or public buildings) also justifies more research in the field of alternative alarm technologies for people who are deaf or hard of hearing.

Given this clear need to obtain a better understanding on the available technologies for alerting people who are hard of hearing or deaf, the Fire Protection Research Foundation at the National Fire Protection Association (NFPA) has initiated a project on this subject, which was awarded to the Division of Fire Safety Engineering at Lund University.

The aim of this project is therefore to develop resources on and provide a review of the currently available alarm and notification technologies for people who are deaf or hard of hearing in case of fire. This includes both a review of their main characteristics and a systematic classification according to their type of stimulus. The use of these technologies is also put in context by reviewing existing regulations, certification and approval processes for devices for the deaf and hard of hearing community. Additionally, the experiences and preferences of people who are deaf or hard of hearing are of interest in order to guide further research in the area. This aim has been achieved both reviewing the scientific literature concerning the main technologies available, as well as the codes and standards they may need to comply with. The experiences and preferences of the target groups were investigated through a survey.

In order to address the aim specified above, three research questions were formulated:

- What are the available alarm and notification technologies for awakening sleeping people who are deaf or hard of hearing?
- What regulations, certification and approval processes are these technologies subject too?
- What are the experiences and preferences of people who are deaf and hard of hearing regarding available alarm technologies?

1.1. Report overview

This report presents the findings of two reviews and a survey. The two reviews are a literature review of the available alarm technologies for awakening sleeping people who are deaf or hard of hearing and a review of codes and standards, which these technologies are subject. The survey was aimed to investigate the experiences and preferences of people who are deaf or hard of hearing.

The report structure is here presented. The first section introduces the topic (Section I: Introduction) and the overall aim of the project. Section II (Method) introduces the method used for both reviews, the templates that were developed to perform the analysis of the material under scrutiny, and the method used for the survey. Section III (Results) presents the results from both reviews based on the template and a suggested classification of technologies. It also provides a summary of the key findings associated with the technologies identified. Selected results from the survey are also included in this section. Section IV (Discussion) provides a critical analysis of the results of the reviews, survey and included literature, as well as the limitations of the current work and the needed future research directions. Section V (Conclusion) presents a final set of considerations concerning alarm technologies for people who are deaf or hard of hearing.

2. Method

It was deemed that a scoping review of the scientific literature, a review of codes and standards, and a survey was best suited to fulfil the research aim and answer the research questions posed in section 1.

2.1. Scoping review of scientific literature

The scoping review has been performed following the PRISMA methodology for scoping reviews approach as presented by Tricco et al. [20]. The aim of the scoping review has been to summarize the findings from the body of knowledge.

To identify relevant literature (or records), five different databases (PsychInfo, PubMed, Scopus, Web of Science and NFPA Research Library & Archives) and one search engine (Google Scholar) were used. Relevant literature included records that deals with the awakening of people who are deaf or hard of hearing. To identify the literature, search strings were developed. The used search strings for the different databases and search engine can be found in Appendix 1. It was anticipated that some publications would not be found through a search in the above-mentioned databases, hence, the reference lists of the full-text screened records were reviewed by title for the identification of relevant additional records (e.g., the so-called "snowball" literature review approach).

The identified literature was then screened for relevance in different stages. The stages include screening the identified records:

- For duplications, removing duplicates.
- By title and abstract, excluding records that were deemed irrelevant given the aim and research questions.
- By full-text, excluding records that were deemed irrelevant given the aim and research questions.

The research process, along with screening criteria, is visualized in Figure 1.

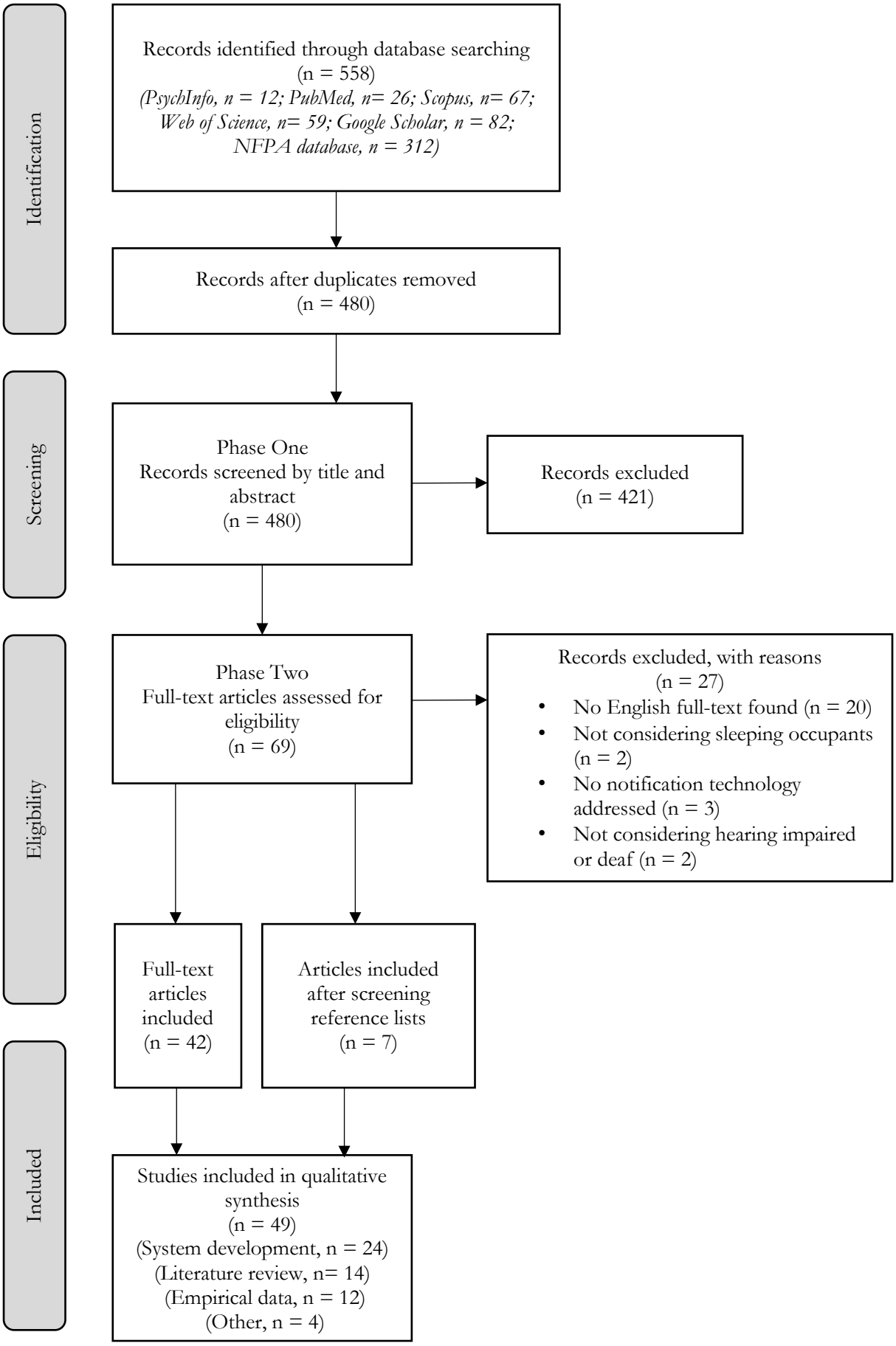

Figure 1. Method flowchart for the scientific literature review.

The qualitative synthesis consisted of gathering relevant information from the identified literature. Relevant information includes:

1. Technologies to awaken people who are hard of hearing or deaf,
2. The effectiveness of these technologies to awaken people who are hard of hearing or deaf,
3. Negative effects on other populations from the use of the technology, and
5. Codes and standards related to the technologies.

In order to facilitate comparison, a project-specific standardized table-reporting template was developed. The template was designed in order to capture the above-mentioned information and facilitate comparison between technologies. The template is shown in Table 1.

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./*

The estimated effectiveness of the different technologies was extracted from the records included in the literature review. In cases where the primary sense addressed by the technology were hearing, only results related to people who are hard of hearing or deaf (real or simulated) were extracted. For other kinds of stimuli, results from other populations were also considered.

2.2. Review of codes and standards

To identify relevant codes and standards that the technologies had to comply with, any mention of codes or standards in the identified literature were noted down. These codes and standards were then reviewed. In order to find more recent codes and standards which may not have been mentioned, a search was conducted in nine major standards institutes. This was mostly based on the codes/standards identified in the scientific literature and the recommendations provided by 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 standards, and American National Standards Institute (ANSI). It should be noted that this review is based on an unstructured search effort and should not be seen as a comprehensive review of all available codes and standards but rather as an attempt to identify the key relevant documents. Therefore, some additional codes and standards may have been excluded from the review. The identified codes and standards were then reviewed based on relevant information regarding requirements or specifications for the notification signal. As such, information regarding reliability, endurance, electrical safety, etc. were not included in this review. As for the case of the review regarding the technologies, a project-specific standardized table reporting template was developed to facilitate the comparison. The template is shown in Table 2.

Table 2. Project specific standardized 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/*

2.3. Survey

To investigate the experiences and preferences of people who are deaf or hard of hearing and other relevant stakeholders, in relation to different alarm technologies, an online survey was developed. Apart from the primary stakeholder, people who are deaf or hard of hearing, the following stakeholders were also reached out:

- Support persons for people who are deaf or hard of hearing, including: Parent of a person who is deaf or hard of hearing, Educator of a person who is deaf or hard of hearing, Service provider/accessibility coordinator for people who are deaf or hard of hearing.
- People working in the domain of fire safety, including: Fire marshals, Firefighters, Fire and life safety educators, etc.

The survey was developed after the initial list of available alarm technologies had been identified through the scoping review of scientific literature. In this way, the authors were able to ask specifically about those technologies. The full extent of the survey can be found in Appendix 2.

The survey was divided into four different parts:

- Background questions
- Experiences of different alarm technologies
- Preferences regarding alarm technologies in their primary residence
- Preferences regarding alarm technologies when visiting hotel or lodging establishment

Regarding experiences of different alarm technologies, the respondents were asked to answer with one of the following options in relation to specific alarm technologies:

1. I have not heard of it
2. I have heard of it, but have not tried/I have heard of it, but have never recommended it
3. I have used it, but don't use it anymore/I have recommended it before, but don't anymore
4. This is what I use/This is what I recommend

To investigate the preferences of people, five point Likert-scale questions were deemed appropriate. Depending on the stakeholder answering the questionnaire, the formulation was altered based on a logic as shown in Appendix 2. The questions used to investigate the preferences in the participants' primary residence were as follows:

1. The fire alarm should wake a person who is deaf or hard of hearing when sleeping in his/her own bed at their primary residence.
2. The fire alarm should be portable so that it can easily be brought on trips.
3. The fire alarm should be able to wake a person who is deaf or hard of hearing no matter where in their primary residence the person may fall asleep.
4. The fire alarm should be incorporated in another device, such as an alarm clock, instead of being a standalone device.
5. One should not need to remember to wear, place, or activate the fire alarm before going to sleep.
6. One should not have to do any maintenance on the fire alarm, such as charge it or change batteries.

7. The fire alarm should be able to connect to smart devices.
8. The fire alarm should wake the person up comfortably.

In relation to hotel or lodging establishment, the participants were asked for their preference in the following items:

1. The hotel manager should provide the deaf or hard of hearing person with an acceptable fire alarm technology in the hotel room to wake them.
2. A person who is deaf or hard of hearing should bring a portable device that works for them to hotel or lodging establishments.
3. The fire alarm technology provided should wake a person who is deaf or hard of hearing when sleeping in the hotel room bed.
4. The fire alarm technology provided should be portable so that it can easily be used in other rooms in the lodging establishment.
5. The fire alarm technology should be able to wake a person who is deaf or hard of hearing anywhere in the hotel room.
6. The fire alarm technology should be incorporated into another device in the hotel, such as an alarm clock, instead of being a standalone device.
7. The deaf or hard of hearing person should not be responsible for wearing, placing, or activating the fire alarm technology before going to sleep in the hotel room.
8. The fire alarm technology provided should not require maintenance by the deaf or hard of hearing occupant, such as charging it.
9. The fire alarm technology should have the ability to connect to smart devices.
10. The fire alarm technology provided should wake the person up comfortably.

The results of the survey were analyzed by means of descriptive statistics.

As stated, the survey was designed as an online survey and was distributed by members in the DARAC committee to organizations and people that might be interested to participate. In total, 75 people participated in the survey, of which 36 were people who were deaf or hard of hearing, 18 people who were support persons for people who are deaf or hard of hearing, and 21 people who worked for or with the fire and rescue service. In the results section, these two groups are separated as they provide unique insights.

2.4. Delimitations

The scope of the study is to identify available technologies, meaning that no effort is 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.

This scoping review does only include technologies that have been scientifically tested on people who are deaf or hard of hearing or on other populations if the primary sense addressed by the technology was not hearing. As such, technologies that exists and may be effective in awakening people who are deaf or hard of hearing will not be covered in this study if scientific testing has not been identified. However, the discussion section contains some speculations regarding emerging and alternative technologies that might be effective and useful for people who are hard of hearing or deaf.

3. Results

This section contains the results from the scientific literature review, the review of codes and standards, and the results from the survey. The results are presented in three different sub-section.

3.1. Identified technologies to wake people who are deaf or hard of hearing

The scientific literature reviewed 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. Table 3 present all technologies identified in the literature review, as well as the primary stimulus they afford, and references to the studies presenting empirical data related to the technology.

The technologies were indeed categorized into four main types of stimulus, namely 1) Audible, 2) Olfactory, 3) Tactile and 4) Visual. Certain types of technologies were investigated in more than one reference, thus the reported information is in that case based on multiple sources of information.

Table 3. Identified technologies to wake people who are deaf or hard of hearing, the primary stimulus afforded, and the references containing empirical data related to the technology.

Technologies identified for awakening people who are hard of hearing or deaf	**Primary stimulus afforded**	**References**
High-frequency alarm	Audible	[11], [12], [13]
Low-frequency alarm	Audible	[11], [12], [13]
Olfactory alarm	Olfactory	[21], [22], [23], [15]
Air movement	Tactile	[24]
Bed shaker	Tactile	[24], [25], [26], [11], [13]
Electric shocks	Tactile	[27]
Hearing-dog robot	Tactile	[28], [29]
Heater	Tactile	[23]
Pager	Tactile	[30]
Phone under pillow	Tactile	[28]
Pillow shaker	Tactile	[12], [13], [11]
Vibrating wristband	Tactile	[28], [30]
Strobe light	Visual	[24], [17], [13], [11], [12], [18], [19]

The technologies identified are here reviewed and presented in a project-specific standardized table format as presented in section 2.1 in order to facilitate comparison. The technologies are presented in different sub-sections depending on what primary stimulus is afforded.

3.1.1. Identified technologies affording audible stimulus

This section presents the results for the two identified technologies affording audible stimulus: High-frequency alarm and Low-frequency alarm.

Table 4. Review of High-frequency alarm.

Technology High frequency alarm
Primary stimulus afforded Audible
Description of the technology The high frequency alarm is the conventional smoke alarm installed in most public and residential buildings. The notification mechanism is often incorporated in the smoke detection device and mounted in the ceiling either outside or in the sleeping area. A high frequency sound can be easily generated using a piezoelectric element which is relatively power efficient [31]. The power efficiency also means that this kind of alarm is easily implemented as a battery-powered device. In this context, 'high frequency' means that the alarm generates sound at a frequency of 2000 Hz or more. As the notification mechanism is typically integrated in the smoke detection device, the notification is hardwired to the smoke detection and is activated as soon as smoke is detected. However, there are also standalone devices that are activated by the sound of a standard smoke alarm. The main rationale for doing this is to offer a signal with either a different frequency or higher sound pressure level than the alarm by which it is activated.
How the technology is used today and its availability As stated, this kind of audible alarm is the one most used and many different manufacturers and models exists. The technology is also relatively cheap and easy to install.
Documented effectiveness for awakening people Du Bois et al. [13] (more details in Ashley [11]) investigated a 3100 Hz alarm, presumably pure tone signal, with a sound pressure level of 81 +- 4 dBA. Twenty-eight subject were involved with a hearing loss between 20-90 dBA over the frequency range 250-8000 Hz. Sleep stage was controlled for and the participants were presented with the stimuli from sleep stage 2, 3, 4 or REM. The reported results were that 57% awoke to the signal. Complementary material [11] also reported that the effectiveness were 0% for 33 people who were deaf, and 92% for 24 hearing able participants. Bruck & Thomas [12] investigated a similar signal, but at different sound pressure levels, as part of a project funded by the NFPA. Thirty-eight participants (16 males, 22 females) with a mean age of 54.4 years and hearing loss between 25-70 dB at 500, 1000, 2000, and 4000 Hz were involved. It was found that 18/32 awoke when presented with the stimuli at or below 75 dBA, 9/32 awoke from higher sound pressure levels, and 5/32 slept through all sound pressure levels.
Possible or documented undesirable consequences for other parts of the population People on the autism spectrum may get disoriented from the sound of an audible alarm [32], especially without proper training. It has also been shown that the high-frequency alarm is not very efficient for other risk-groups, including children and alcohol-impaired populations [33].

Table 5. Review of Low-frequency alarm.

Technology Low frequency alarm
Primary stimulus afforded Audible
Description of the technology This technology is similar to the high-frequency alarm, with the difference that the frequency used is lower. "Low-frequency" in this context refers to signals with a frequency of around 520 Hz. The frequency has been proven to be more difficult to implement in a battery powered device due to its relatively high power consumption [31]. As the notification mechanism is typically integrated in the smoke detection device, the notification is hardwired to the smoke detection and is activated as soon as smoke is detected. However, there are also standalone devices that are activated by the sound of a standard smoke alarm. The main rationale for doing this is to offer a signal with either a different frequency or higher sound pressure level than the alarm by which it is activated.
How the technology is used today and its availability There are manufacturers supplying a low-frequency alarm for AC voltage installation integrated with smoke detection, as well as standalone devices. Standalone devices often include more stimuli than the low-frequency audible signal, e.g., flashing lights or bed shaker for installation on the bedside table.
Documented effectiveness for awakening people Du Bois et al. [13] (more details in Ashley [11]) investigated a 400-500 Hz, presumably pure tone signal, with a sound pressure level of 80 dB at the pillow. A total of 13 subject were involved, all with a hearing loss between 20-90 dB over the frequency range 250-8000 Hz. Sleep stage was controlled for and the participants were presented with the stimuli from sleep stage 2, 3, 4 or REM. The reported results were that 92% awoke to the signal. Complementary material [11] also reported that the effectiveness were 11% for 18 people who were deaf, and 100% for 5 hearing able participants. Bruck & Thomas [12] investigated a 520 Hz and a 400 Hz square wave signal in a T-3 pattern at different sound pressure levels, as part of their project funded by the NFPA. Thirty-eight participants (16 males, 22 females) with a mean age of 54.4 years and hearing loss between 25-70 dB at 500, 1000, 2000, and 4000 Hz were involved. For the 520 Hz signal it was found that 22/36 awoke at 55 dBA, 5/36 at 65 dBA, 6/36 at 75 dBA, 1/36 at 85 dBA, 2/36 at 95 dBA, and that no participant slept through all sound pressure levels. The 400 Hz signal was found to be less effective, with 32/37 awoken when presented with the stimuli at or below 75 dBA, 3/37 awoke from higher sound pressure levels, and 2/37 slept through all sound pressure levels. Bryan et al. [18] investigated a low frequency 520 Hz square wave and voice annunciation device (sound pressure level was not reported). They found that, out of 19 subjects who were all profoundly deaf, only two awoke from REM sleep when exposed to the audible alarm.
Possible or documented undesirable consequences for other parts of the population Not identified

3.1.2. Identified technologies affording olfactory stimulus

This section presents the results for the identified technology affording olfactory stimulus: Olfactory alarm.

Table 6. Review of Olfactory alarm.

Technology Olfactory alarm
Primary stimulus afforded Olfactory
Description of the technology Olfactory alarms typically depend on a liquid mixed with fragrance that is sprayed into the room of the sleeping occupant. Depending on the spray technology used and the configuration of the sleeping area, it might be possible to integrate the spray mechanism in the smoke detection device. A spray device is also relatively power efficient, opening up for the possibility of a battery-powered device. There are many possibilities for connecting this kind of device to the fire alarm, including sound detection, wireless signals, and hardwiring.
How the technology is used today and its availability There are some commercially available examples of smell-based alarm clocks for non-emergency applications (for example [34]), while commercial products for emergency applications were not identified.
Documented effectiveness for awakening people Research on smell for fire notification falls into two different categories: research investigating the use of smell-based devices for awakening people, and research investigating the arousal from the smell of smoke. Lynch [21] presents research related to both categories. In the study, smoke (in the form of food additive) and citrus odor was tested on ten adults aged between 26 and 60 years old. It is reported that two of the participants awoke from stage 2 sleep when presented with smoke odor, but none awoke from the citrus smell. Carskadon and Herz [22] investigated two other odors, peppermint and pyridine (fish-like smell), at four different concentrations. They investigated the effectiveness on three males and 2 females aged 20 to 25 years old when presented with the stimuli in stage 1, 2, 4 and REM sleep. They concluded that the odors were effective at awakening from stage 1 sleep, but less effective for deeper stages of sleep. The peppermint odor elicited no behavioral response from deeper stages of sleep, while the more unpleasant odor of pyridine elicited some response, but for less than 50 % of participants. Kahn [23] reported on the awakening of 12 male undergraduate students (mean age 21.3) from smoke odor. The smoke odor was simulated using three paint coated 150 W light bulbs. It is reported that the smoke odor was 'noticeable' at the pillow within 1.5 minutes of system activation. Only three out of twelve subjects awoke (measured with behavioral response) from the stimuli. The most recent research identified was conducted by Bruck and Brennan in 2001 [15]. In this study, smoke odor was dispersed via a duct and fan. Seventeen young adults, aged 18-16, were exposed to the stimuli. It is reported that 59 % awoke from the stimuli, and that it was considerably more effective for females (80 %) than for males (29 %).
Possible or documented undesirable consequences for other parts of the population People may regularly suffer from congested nose, which would render the technology non-efficient. It is also known that elderly, especially people suffering from Parkinson's disease, suffer from a decline in olfactory sensibility [35]. Allergies might also pose a problem for these kinds of technologies.

3.1.3. Identified technologies affording tactile stimulus

This section presents the results for the nine identified technologies affording tactile stimulus: Air movement, Bed shaker, Electric shocks, Hearing-dog robot, Heater, Pager, Phone under pillow, Pillow shaker, and Vibrating wristband.

Table 7. Review of Air movement.

Technology Air movement
Primary stimulus afforded Tactile
Description of the technology Air movement has been proposed as one technology to awaken people who are deaf or hard of hearing. The technology can be configured in many different ways; one of those is by installing fans near the sleeping person that is activated by the fire alarm. Due to the specific requirements of placements of fans, it is not suited to be integrated with the detection mechanism of the fire alarm. To produce a reasonable amount of air movement, the fans cannot be powered by battery and this technology should therefore require fixed installation. There are many possibilities for connecting this kind of device to the fire alarm, including sound detection, wireless signals, and hardwiring.
How the technology is used today and its availability Not identified
Documented effectiveness for awakening people Underwriters laboratories (UL) published a report in 1991 [24] that investigated the effectiveness of air movement to wake up sleeping people. The researchers did not check for sleep stage, and the research subjects were tested between 1 am and 4 am. The sample consisted of 69 legally deaf, unmedicated subjects aged between 10 and 69 years old. It is reported that 55 % of the participants awoke from an air speed of 140 ft./min (approximately 0.71 m/s) and 81% awoke from 270 ft./min (approximately 1.37 m/s). The results also show that it was more effective for adults, as all 10 of the adults tested (100%) awoke from 270 ft./min air velocity.
Possible or documented undesirable consequences for other parts of the population Not identified

Table 8. Review of Bed shaker.

Technology Bed shaker
Primary stimulus afforded Tactile
Description of the technology Typically, a bed shaker is connected to a device that is put on the bedside table. Bed shakers typically require AC voltage and battery backup is seldom offered, presumably due to the energy consumption. The bed shaker is most often connected to a device that is to be placed at the bedside table, which detects the sound of a regular smoke alarm and activates the bed shaker upon detection. It would be possible to connect the bed shaker directly to the fire alarm system, but no commercial example of this device could be found.
How the technology is used today and its availability The term bed shaker is often used interchangeably with pillow shaker. These kinds of devices are offered from a wide variety of manufacturers. It also seems as though bed shakers are the preferred choice if an alarm clock with audible alarm is deemed unsuitable, with many manufacturers offering bed shaker alarm clocks. Even though fire alarm specific devices exist, many seem to incorporate other functionalities as well, such as other sound notification and alarm clock.
Documented effectiveness for awakening people Underwriters Laboratories [24] conducted an experiment involving bed shakers. The bed shaker consisted of a cylindrical vibration device with a cylinder displacement of 1/8 inch and a vibration frequency of 100 Hz. The device was placed under the pillow or under the mattress. Sleep stage was not controlled for. Subjects included 20 legally deaf adults as well as 77 deaf children between 10-19 years old. It was reported that 95% of the adults awoke from a four-minute long presentation of the stimuli, and that 77-100% of the younger awoke, with different effectiveness depending on age group. A couple of years later, Murphy et al. [25] conducted experiments using a commercial bed shaker. The study involved 11 hard of hearing adults aged 20-76 years, with hearing loss ranging from slight to profound, and 16 young adult university students with self-reported normal hearing. The student wore earplugs to simulate hearing loss. Eighty-seven percent of the hard of hearing awoke from REM sleep when presented with the stimuli, and 70% awoke from slow-wave-sleep. The results from the normal-hearing group were 92% and 76% respectively. It is also worth noting that the hard of hearing group required longer time to wake up from the stimuli, with 19% requiring more than one minute. Roby [26] conducted a smaller study involving 13 college aged deaf students. It was reported that ten of those awoke from the vibrations from a variable bed shaker. In Du Bois et al. [13] (more details in Ashley [11]), a commercial bed shaker was tested. It is assumed that the intensity of the bed shaker was not altered from how it was configured when bought. However, the vibration pattern of the bed shaker was altered to be intermittent (T-3 pattern) as some of the participants reported that they used this exact bed shaker as an alarm clock (which is its intended use). It was feared that having the same signal as their original alarm clock would result in invalid results. Results from using both a continuous (as bought) and intermittent vibration pattern were reported. Three groups of participants were involved: 26 hearing able adults, 22 adults with hearing loss between 25-90 dBA, and 30 adults who were deaf. Results show that the continuous bed shaker was effective in approximately 90% of trials, with marginally less effectiveness being reported for the hard of hearing group. The intermittent bed shaker awoke the participant in 100% of the trials. Bruck and Thomas [12] conducted experiments involving 38 hard of hearing subjects (16 males and 22 females) with a hearing loss between 25 and 70 dBA. Sleep stage was controlled for and the participants were woken from either stage 3 or 4 sleep. The bed shaker used was a commercially available bed shaker but was modified so that the intensity could be altered. It was reported that 28/35 participants awoke when presented with a vibration intensity that was at or below the "off-the-shelf" configuration, 3/35 awoke when the intensity was raised, and 4/35 slept through all intensity levels. It was also reported that the bed shaker was significantly less effective for those over 60 years old. Lastly, Bryan et al. [18] investigated an intermittent bed shaker. They found that, out of 19 subjects who were all profoundly deaf, all awoke from REM sleep when exposed to the vibrating alarm. It was also concluded that the participants awoke significantly quicker from the intermittent bed shaker than from a strobe.

Conclusively, bed shakers seem to be a reliable way of waking up people who are deaf or hard of hearing. However, it is very difficult to compare the results from different studies due to differences in experimental procedures. Importantly, it is difficult to know what intensity of vibration the sleeping participant perceived since the studies used different methods for measuring this, if measuring at all.
Possible or documented undesirable consequences for other parts of the population Not identified

Table 9. Review of Electric shocks.

Technology Electric shocks
Primary stimulus afforded Tactile
Description of the technology Electric shocks can be delivered to people using sensors attached to the skin. To induce the electric shocks, the electrodes fitted to the occupant needs to get a signal from a device. This device could possibly be attached to the sleeping occupant as well, or be placed on for example the bedside table. This is the only identified application. There are many possibilities for connecting this kind of device to the fire alarm, including sound detection, wireless signals, and hardwiring.
How the technology is used today and its availability Not identified.
Documented effectiveness for awakening people Pisano et al. [27] presents research on painful electric shocks to induce arousal in sleeping adults. Eight healthy subjects (aged 20-45) volunteered to take part in the study. The electric shocks were delivered through electrodes mounted on one of the participants' forearms. Mean threshold of arousal was reported to be 50 Volts (short durations). Even though electric shocks of this voltage and current may be harmless (but painful) for humans, it is deemed to be of little use as a notification technology due to ethical considerations and their practical implementation.
Possible or documented undesirable consequences for other parts of the population Not identified.

Table 10. Review of Hearing-dog robot.

Technology Hearing-dog robot
Primary stimulus afforded Tactile
Description of the technology Hearing-dogs are used by some people who are deaf or hard of hearing to make them aware of sounds in the environment through touch. This technology mimics the behaviors of a hearing-dog. The robot detects the sound of the alarm and locates the occupant. The occupant is then notified by the robot that 'bumps' into them. No commercially available products of this kind were identified, but the robot could be activated either through recognizing the sound of an audible fire alarm, or through signals transmitted via Wi-Fi, Bluetooth or similar.
How the technology is used today and its availability This technology is not commercially available, but a prototype has been developed by a research group in Japan [28], [29].
Documented effectiveness for awakening people As stated, this technology has been developed by a research group in Japan and they report on the effectiveness at awakening people in two different publications. Sekiya et al. [28] report on an experiment involving ten participants (mean age 23.2 years) where hearing loss was simulated using earplugs that reportedly "completely muffled sounds more than 30 dB". The robot was configured to bump the bed in which the participants were sleeping with 12 N or 26 N with 1 or 4 seconds intervals. Each participant was exposed to 4 trials. The results were that all participants awoke in under 20 seconds. The other experiment [29] included 16 participants (14 male, 2 female, age 20-25 years). Hearing loss and bumping procedure was the same as in the previous experiment. Similarly, all participants awoke.
Possible or documented undesirable consequences for other parts of the population Not identified.

Table 11. Review of Heater.

Technology Heater
Primary stimulus afforded Tactile
Description of the technology An element is installed near the sleeping person, and is activated and starts to radiate heat once the alarm is activated. Due to the requirements of the placement of the heater, it is not possible to integrate the smoke detection mechanism in the same device. To produce the required radiant heat levels, it is not possible to power the device via batteries. To produce the required radiative heat, the device would need to be of considerable size, making it less portable. Due to the relatively slow transportation and buildup of heat, it is also deemed less relevant in the context of emergency notification. There are many possibilities for connecting this kind of device to the fire alarm, including sound detection, wireless signals, and hardwiring.
How the technology is used today and its availability Not identified.
Documented effectiveness for awakening people Research regarding the effectiveness of heat-based notification is scarce. However, one study by Kahn [23] report an experiment involving 12 male undergraduate students (mean age 21.3 years). A 750 W radiant heater placed on the wall beside the pillow was used in the experiment. The heater caused the temperature at the nearest edge of the bed to rise from 22C to 30C within 10 minutes, and would reach 36C after 20 minutes. It is reported that three out of twelve participants awoke from the stimuli.
Possible or documented undesirable consequences for other parts of the population While not related to a specific group of people, a possible malfunction in the heating device might become a fire hazard.

Table 12. Review of Pager.

Technology Pager
Primary stimulus afforded Tactile
Description of the technology A pager is wireless device that receives messages and alerts the user via text message and/or vibrations. For a fire safety application, the device can be configured to receive signals from a smoke alarm and activate the vibration. The pager could then be placed under the pillow to act as a pillow shaker. There are many possibilities for connecting the pager to the smoke alarm, and the most intuitive would probably be to transmit a signal wirelessly, as is the case for pagers used in other contexts.
How the technology is used today and its availability No commercial product that implements a pager with vibration as an emergency awakening technology was identified (presumably because the pillow or bed shaker is seen as a better option). There are however commercially available examples of wearable devices with vibration for non-emergency applications.
Documented effectiveness for awakening people Roby [30] presents a pilot study where a pager with vibrational capabilities was tested for its effectiveness at awakening sleeping college aged subjects who were deaf. It is reported that 4 out of 13 attempts were effective. It was not clear where the pager was placed, nor the characteristics of the vibrations.
Possible or documented undesirable consequences for other parts of the population Not identified

Table 13. Review of Phone under pillow.

Technology Phone under pillow
Primary stimulus afforded Tactile
Description of the technology The notification is emitted from a phone placed under the pillow of the sleeping person. The phone emits vibration through the displacement of a weight inside the device. One way of accomplishing this is by mounting an off-center weight to the shaft of a small electric motor, but other technologies are available as well. Because the phone is placed under the pillow, it might not be able to detect the sound of a regular audible smoke alarm reliably. Other means of connectivity involve Wi-Fi or Bluetooth, but these may also be obstructed by the pillow. As the notification technology is embedded in the phone, it offers great portability.
How the technology is used today and its availability There are apps available for smart devices that listens to the alarm and produces vibrations upon detection. There are also regular audible smoke alarms that offers connectivity to the phone via Wi-Fi. However, this functionality should be seen as complementary and cannot reliably replace the notification through audible stimuli embedded in the smoke detector itself.
Documented effectiveness for awakening people Sekiya et al. [28] primarily investigated the use of their developed hearing-dog robot, but does also report on the effectiveness of a vibrating phone placed under the pillow for awakening people for comparison. In their study, hearing impairment was simulated using earplugs, which completely muffled sounds more than 30 dBA. Ten participants with a mean age of 23.2 years were tested. The phone placed under the pillow was said to be effective in nine out of ten cases.
Possible or documented undesirable consequences for other parts of the population Could pose a fire hazard.

Table 14. Review of Pillow shaker.

Technology Pillow shaker
Primary stimulus afforded Tactile
Description of the technology Typically, a pillow shaker is connected to a device that is put on the bedside table. Pillow shakers typically require AC voltage and battery backup is seldom offered, presumably due to the energy consumption. The pillow shaker is most often connected to a device that is to be placed at the bedside table, which detects the sound of a regular smoke alarm and activates the pillow shaker upon detection. It would be possible to connect the pillow shaker directly to the fire alarm system, but no commercial example of this could be found.
How the technology is used today and its availability The term pillow shaker is often used interchangeably with bed shaker. These kinds of devices are offered from a wide variety of manufacturers. It also seems as though the devices are the preferred choice if an alarm clock with audible alarm is deemed unsuitable, with many manufacturers offering bed or pillow shaker alarm clocks. Even though fire alarm specific devices exist, many seem to incorporate other functionalities as well, such as other sound notification and alarm clock.
Documented effectiveness for awakening people Only one study investigating the effectiveness of pillow shakers could be identified, namely the NFPA-funded study by Bruck and Thomas [12]. Bruck and Thomas conducted experiments involving 38 hard of hearing subjects (16 males and 22 females) with a hearing loss between 25 and 70 dBA. Sleep stage was controlled for and the participants were woken from either stage 3 or 4 sleep. The pillow shaker used was a commercially available pillow shaker but was modified so that the intensity could be altered. It was reported that 25/30 participants awoke when presented with a vibration intensity that was at or below the "off-the-shelf" configuration, 4/30 awoke when the intensity was raised, and 1/30 slept through all intensity levels. Interestingly, Du Bois et al. [13] had an original intention of including a pillow shaker in their study, but it was excluded because it was deemed non-reliable as it frequently moved out of its place when it vibrated [11]. The participants who tested the device also complained about the loud noise it generated, making it uncertain whether people woke up from the vibrations or the sound.
Possible or documented undesirable consequences for other parts of the population Not identified.

Table 15. Review of Vibrating wristband/watch.

Technology Vibrating wristband/watch
Primary stimulus afforded Tactile
Description of the technology The device is worn on the wrist and emits vibration through the displacement of a weight inside the device. One way of accomplishing this is by mounting an off-center weight to the shaft of a small electric motor, but other technologies are available as well. Wearable devices like these are small to allow for portability and comfort and are powered via batteries. In recent years, smart wearable devices that connect to your phone or to Wi-Fi have become more common on the market [36]. Technological advances open up for the possibility to implement sound recognition within the device itself, which could listen for the sound of a regular audible smoke alarm. In the era of Internet of Things (IoT), it is also possible to connect the device to a smart smoke alarm [37].
How the technology is used today and its availability No commercial product that implements wearable devices with vibration as an emergency awakening technology was identified. There are some commercially available examples of wearable devices with vibration for primarily non-emergency applications [38].
Documented effectiveness for awakening people Sekiya et al. [28] primarily investigated the use of their developed hearing-dog robot, but does also report on the effectiveness of a wearable device for awakening people as comparison. In their study, hearing impairment was simulated using earplugs that completely muffled sounds more than 30 dBA. Ten participants with a mean age of 23.2 years were tested. The wristband was said to be effective in eight out of ten cases. Roby [30] conducted a pilot test involving three deaf college aged subjects, and none were awoken by a vibrating watch. However, it was not clear whether the watch was activated or not.
Possible or documented undesirable consequences for other parts of the population Some people might find it uncomfortable to sleep with a wrist-mounted wearable device. This might lead them to take it off during nighttime.

3.1.4. Identified technologies affording visual stimulus

This section presents the results for the identified technology affording visual stimulus: Strobes.

Table 16. Review of Strobe light.

Technology Strobe light
Primary stimulus afforded Visual
Description of the technology Strobe lights have long been used as a complement to the traditional audible fire alarm [12]. Strobes are usually securely mounted to a wall or ceiling or integrated in the smoke detection device. Typically, the strobe is hardwired to ensure that it has enough power, but could also be battery powered for increased portability. Typically, the strobe is hardwired to the smoke alarm to ensure reliable activation.
How the technology is used today and its availability Strobe lights are widely commercially available with many manufacturers all over the world. It is sometimes required in public buildings and especially in areas where people are expected to be sleeping.
Documented effectiveness for awakening people Throughout the years, there have been several studies regarding the effectiveness of strobe-like devices for waking up people who are deaf or hard of hearing. One of the first were Nober et al. [39] which investigated a 100 cd strobe with a frequency of 75 flashes per minute (3.3 lumen-sec/m at the pillow). The study did not control for sleep stage but reported that it was 92 % effective among 12 deaf adults. The following year, UL [24] conducted an experiment involving 1) 22 people who were deaf and aged 20-65+, 2) 58 students who were deaf and aged 13-19, 3) 14 students who were deaf and aged 10-12, and 4) medicated adults. The study utilized a strobe with an intensity of 110 cd and a flashing frequency of 1 Hz. The reported effectiveness was 100% for the adults, 91% for the older students, 86% for the younger students, and 28% for the medicated. These two studies showed a promising effectiveness of the strobe signal for awakening this at-risk population and prompted changes in the regulatory field. Bowman et al. [17] continued the research on strobes investigating the effectiveness of a strobe of 75 cd, 16 mu F, 19.9 Lux, within 75 cm of the pillow. Subjects consisted of thirteen fully hearing able females over the age of 18. In this study, controls for sleep stage were made and effectiveness was investigated for sleep stage 3 and 4, and REM sleep. It was concluded that 35% awoke when presented with the stimuli in either stage 3 or 4 sleep, and 45% awoke from REM sleep. This study contradicted the earlier studies and showed that strobes may in fact not be a very effective means of awakening people, at least from deeper stages of sleep. Du Bois et al. [13] (more details in Ashley [11]) investigated the effectiveness of a strobe with 110 cd and a flashing frequency of 1 Hz, all in line with contemporary legislation. Sleep stage was controlled for and the participants were awoken from either stage 2, 3, 4 or REM sleep. Three different groups were selected as research subjects: 1) 35 deaf adults, 2) 29 hard of hearing adults (hearing loss between 25-90dB over the frequency range 250-800 Hz), and 3) 31 adults without hearing loss. The reported effectiveness were 57%, 34% and 32% respectively. This is very much in line with the findings by Bowman et al. [17]. Bruck & Thomas [12] conducted research on strobes as part of a research project funded by the NFPA. They utilized a strobe with intensities exceeding the requirements in NFPA 72, with an intensity of 177 cd, 210 cd and 420 cd. The flashing frequency was 2 Hz in a T-3 pattern. The participants were 38 in total: 16 males and 22 females, with a mean age of 54.4. All participants had a hearing loss between 25 and 70 dB at frequencies 500, 1000, 2000 and 4000 Hz. Sleep stage was controlled for and participants were presented with the stimuli in either stage 3 or 4 sleep. The results show that 10/37 awoke to the 170 cd strobe, and almost half (16/37) slept through even the highest intensity strobe. The most recent research identified was conducted by Bryan et al. [18]. They tested a 177 cd strobe mounted just three feet (91 cm) from the pillow. The researchers hypothesized that the reason strobes had been shown to be ineffective in previous studies was that it had been mounted high up on the walls [19]. In their study, they found that, out of 19 subjects who were all profoundly deaf, all awoke from REM sleep when exposed to the strobe. However, the time it took for awakening was significantly longer than for an intermittent bed shaker that was also tested.
Possible or documented undesirable consequences for other parts of the population

A common concern regarding strobes is that it will have a negative effect on people suffering from epilepsy [32]. Flashing frequencies of approximately 1 Hz s said to mitigate these issues.

The study by UL [24] found that some participants were blinded and could not perform even the simplest tasks. They also found that slower than 1 Hz (in a dark room) led to confusion and disorientation.

Depending on how a person sleeps (e.g. blocking their eyes by sleeping on their stomach or sleeping under the sheets), they may have trouble in registering the stimuli from the strobes.

3.1.5. Summary of all identified technologies to wake sleeping people who are deaf or hard of hearing

This section presents a summary of the main characteristics of the identified alarm technologies to wake sleeping people who are deaf or hard of hearing. The summary is structured in a similar way as the tables presented in section 3.1 but presenting the findings in a qualitative fashion. The summary can be found in Table 17.

Table 17. Summary of all 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. ([11], [12], [13])	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. ([11], [12], [13])	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 odor used. ([21], [22], [23], [15])	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. ([24])	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. ([24], [25], [26], [11], [13])	Not identified.
Electric shocks	Tactile	Electric shocks delivered via electrodes attached to the skin.	Not found.	Research is limited. ([27])	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. ([28], [29])	Not identified.
Heater	Tactile	Radiative heating device installed by the bed.	Not found.	Limited effectiveness, but research is	Potential fire hazard.

				also limited. ([23])	
Pager	Tactile	Small portable device that vibrates when activated.	Widely used, but not for emergency alarm purposes and awakening.	Research is limited. ([30])	Not identified.
Phone under pillow	Tactile	Regular cell phone installed under the pillow. Vibrates when activates and functions as a pillow shaker.	Widely used, but not for emergency alarm purposes and awakening.	Research is limited. ([28])	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], [13], [11])	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. ([28], [30])	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. ([24], [17], [13], [11], [12], [18], [19])	Depending on the flashing frequency, it could cause epileptic seizures or disorientation.

3.2. Codes and standards concerning devices for waking up people that are deaf or hard of hearing

Codes and standards concerning devices for waking up people that are deaf or hard of hearing were identified from the publications found in the scientific literature review, as well as an unstructured search in a set of key well-known standardization organizations. A total of 19 codes or standards were identified. According to NFPA, *"A code is a model, a set of rules that knowledgeable people recommend for others to follow. It is not a law, but can be adopted into law. A standard tends be a more detailed elaboration, the nuts and bolts of meeting a code"*. Table 18 presents the codes and standards identified and deemed relevant in this research. The specific technology, according to Table 3, that is addressed by the code or standard is also presented.

Table 18. Identified codes and standards, as well as which technology they address.

Name	**Technologies addressed**
ANSI/ASA S3.41-2015 "Audible Emergency Evacuation (E2) and Evacuation Signals with Relocation Instructions (ESRI)" [40]	High-frequency alarm Low-frequency alarm
AS 1603.17:2020 "Automatic Fire Detection And Alarm Systems Warning Equipment For People With Hearing Impairment" [41]	High-frequency alarm Low-frequency alarm Bed shaker Pillow shaker Strobe light
AS 3786:2014 "Smoke alarms using scattered light, transmitted light or ionization" [42]	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" [43]	Bed shaker Pillow shaker
EN 14604:2005 "Smoke alarm devices" [44]	High-frequency alarm
EN 54-23:2010 "Fire detection and fire alarm systems - Part 23: Fire alarm devices - Visual alarm devices" [45]	Strobe light
EN 54-3:2014+A1:2019 "Fire detection and fire alarm systems - Part 3: Fire alarm devices – Sounders" [46]	High-frequency alarm Low-frequency alarm
FM 3150 "Audible Notification Appliances for Automatic Fire Alarm Signaling" [47]	High-frequency alarm
FM 3155 "Public Mode Visible Signaling Appliances for Automatic Fire Alarm Signaling" [48]	Strobe light
International Building Code (IBC) [49]	High-frequency alarm Low-frequency alarm Strobe light
ISO 8201:2017 "Alarm systems — Audible emergency evacuation signal — Requirements" [50]	High-frequency alarm Low-frequency alarm Bed shaker Pillow shaker Strobe light
NFPA 101 "Life Safety Code" [16]	High-frequency alarm Low-frequency alarm Strobe light
NFPA 72 "National fire alarm and signaling code" [51]	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" [52]	Strobe light
UL 1971 "Standards for safety – Signaling devices for the hearing impaired" [53]	Bed shaker Pillow shaker Air movement Strobe Light

UL 217 "Standards for safety - Smoke alarms" [54]	High-frequency alarm Low-frequency alarm
UL 268/ULC-S529 "Smoke detectors for fire alarm systems" [55]	High-frequency alarm Low-frequency alarm
UL 464/ULC-S525 "Standards for safety - Audible Signaling Devices for Fire Alarm and Signaling Systems, Including Accessories" [56]	High-frequency alarm Low-frequency alarm
ULC-S531 "Standard for smoke alarms" [57]	High-frequency alarm Low-frequency alarm

The codes and standards identified are here reviewed and presented in a project-specific standardized format as described in section 2.2 in order to facilitate comparison. Reviews are presented in Table 19 through Table 37.

Only information deemed relevant by the authors has been extracted from the standards. This includes information related to the notification technology for example. As such, electrical safety, detection technology, reliability etc. have not been extracted as it is outside the scope of this report. This review should not be read as a comprehensive summary of the identified codes and standards. For complete information, the reader is directed to the actual code or standard.

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.

Table 19. Review of ANSI/ASA S3.41-2015.

Type	Standard
Name	ANSI/ASA S3.41-2015 "Audible Emergency Evacuation (E2) and Evacuation signals with Relocation Instructions (ESRI)" [40]
Edition	July 2015
First issued	N/A
Region	U.S.A
Scope	The standard specifies characteristics of acoustics signals used for emergency evacuation.
Notification technology requirements	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 1000-4000 Hz.

Table 20. Review of AS 1603.17:2020.

Type	Standard
Name	AS 1603.17:2020 "Automatic fire detection and alarm systems – Part 17: Warning equipment for people with hearing impairment." [41]
Edition	Third edition, June 2020
First issued	2011
Region	Australia
Scope	The standard specifies requirements for warning equipment aimed towards the hard of hearing population, and in particular to awaken members of that population.
Notification technology requirements	For visual alarm devices, the reader is referred to AS ISO 7240.23. For vibrating pad, for awakening, the reader is referred to the testing procedure specified in BS 5446-3:2015 Annex G. However, 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. For audible alarm devices, the reader is referred to AS ISO 7240.23 or AS 3786.

Table 21. Review of AS 3786:2014.

Type	Standard
Name	AS 3786:2014 "Smoke alarms using scattered light, transmitted light or ionization" [42]
Edition	Third edition, December 2014
First issued	1990
Region	Australia
Scope	The standard contains 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.
Notification technology requirements	The signal pattern is specified to be according to ISO 8201 or ISO 7731. An optional specification is provided. When the alarm is activated, the sound pressure level is 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 meter distance.

Table 22. Review of BS 5446-3:2015.

Type	Standard
Name	BS 5446-3:2015 "Detection and alarm devices for dwellings – Part 3: Specification for fire alarm and carbon monoxide alarm systems for deaf and hard of hearing people" [43]
Edition	Second edition, February 2015
First issued	April 2005
Region	Great Britain
Scope	The standard specifies requirements for fire and/or carbon monoxide alarm systems for people who are deaf and hard of hearing in dwellings.
Notification technology requirements	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. For other specifications, the reader is referred to BS EN 54-23:2010. 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 second followed by an inactive period of 2+-1.5 seconds. 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 grams (specifications of the test is provided in Annex G.2), 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 second. Low frequency sounders intended for bedroom use should produce a sound pressure level of at least 75 dBA at 1 meter distance, but no more than 110 dBA. For battery-powered devices, the sound pressure level is allowed to decrease by 3 dBA after 4 minutes of activation and no decrease in sound pressure level is allowed after 1 minute of activation. For main-powered devices, no decrease in sound pressure level is allowed after 4 minutes of activation. 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. Table A.1 specifies which components (low frequency sounder, visual alarm, vibrating pad, etc.) needs to be included in the alarm depending on the application. Annex G contains specifications for the different tests that are mandatory for vibrating pads, including tests for the characterization of the vibration.

Table 23. Review of EN 14604:2005.

Type	Standard
Name	EN 14604:2005 "Smoke alarm devices" [44]
Edition	21st March 2005
First issued	N/A
Region	Europe
Scope	Applies to smoke alarms intended for household or similar residential application.
Notification technology requirements	For battery-powered and mains-powered alarms, the sound output shall be at least 85dBA, measured at 3 meters from the appliance. The maximum sound output shall not exceed 110 dBA, measured at 3 meters from the appliance. The maximum nominal frequency shall not exceed 3500 Hz.

Table 24. Review of EN 54-23:2010.

Type	Standard
Name	EN 54-23:2010 "Fire detection and fire alarm systems - Part 23: Fire alarm devices - Visual alarm devices" [45]
Edition	First edition, March 2010
First issued	March 2010
Region	Europe
Scope	This standard specifies requirements, test methods and performance criteria for fixed installation visual alarm devices.
Notification technology requirements	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.

Table 25. Review of EN 54-3:2014+A1:2019.

Type	Standard
Name	EN 54-3:2014+A1:2019 "Fire detection and fire alarm systems - Part 3: Fire alarm devices – Sounders" [46]
Edition	Third edition, April 2019
First issued	2001
Region	Europe
Scope	This standard specifies requirements, test methods and performance criteria for fixed installation (in comparison to EN 14604:2005) fire alarm sounders.
Notification technology requirements	It is stated in the standard that some European countries have specifications regarding the frequencies of sound and sound pattern. Annex D contains further information on this. 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.

Table 26. Review of FM 3150.

Type	Standard
Name	FM 3150 "Audible Notification Appliances for Automatic Fire Alarm Signaling" [47]
Edition	September 2020
First issued	N/A
Region	U.S.A
Scope	The standard contains performance requirements for electronically powered horns and bells (not speakers) for sounding alarms.
Notification technology requirements	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 meters from the device, and maximum 120 dBA at the minimum hearing distance from the device. These requirements relates to public mode.

Table 27. Review of FM 3155.

Type	Standard
Name	FM 3155 "Public Mode Visible Signaling Appliances for Automatic Fire Alarm Signaling" [48]
Edition	September 2020
First issued	N/A
Region	U.S.A
Scope	The standard contains performance requirements for public mode visible signaling appliances for fire signaling. Examples of such includes high intensity strobes.
Notification technology requirements	The visible alarm appliances are specified to flash with a frequency of no more than 2 Hz and no less than 1 Hz. The color 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, 27.1, and 27.4 in ANSI/UL 1971-2013.

Table 28. Review of IBC.

Type	Code
Name	International Building Code (IBC) [49]
Edition	2021
First issued	2003
Region	International
Scope	The code specifies regulations related to fire safety. Chapter 9 of the code contains regulations related to fire alarms.
Notification technology requirements	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 signaling 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.

Table 29. Review of ISO 8201:2017.

Type	Standard
Name	ISO 8201:2017 "Alarm systems – Audible emergency evacuation signal – Requirements." [50]
Edition	Second edition, November 2017
First issued	1987
Region	International
Scope	The standard specifies the requirements for audible alarm signals.
Notification technology requirements	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 noted in the standard that the signal level may not be adequate to awaken all sleeping occupants. 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.

Table 30. Review of NFPA 101.

Type	Code
Name	NFPA 101 "Life safety code" [16]
Edition	2021, 30th of August 2020
First issued	1927
Region	U.S.A
Scope	The purpose of NFPA 101 is to provide minimum requirements for life safety in case of fire and other emergencies.
Notification technology requirements	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).

Table 31. Review of NFPA 72.

Type	Code
Name	NFPA 72 "National fire alarm and signaling code" [51]
Edition	2019
First issued	1993
Region	U.S.A
Scope	Applies 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.
Notification technology requirements	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 +- 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 color 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 meters (16 feet) of the pillow. Tactile appliances is permitted if used in addition to audible and/or visual notification appliances. The tactile appliance shall meet the requirements in UL 1971 or equivalent. 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.

Table 32. Review of UL 1638 / CAN/ULC-S526.

Type	Standard
Name	UL 1638 /CAN/ULC-S526 "Standards for safety – Visible signaling devices for Fire Alarm and Signaling Systems, Including accessories" [52]
Edition	5th edition, (January 28th 2016) including revisions dated 6th of September 2017.
First issued	N/A
Region	U.S.A / Canada
Scope	Applies to visual signaling devices.
Notification technology requirements	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.

Table 33. Review of UL 1971.

Type	Standard
Name	UL 1971 "Standards for safety – Signaling devices for the hearing impaired" [53]
Edition	Third edition (November 29th 2002) including revisions dated 29th of August 2018.
First issued	June 1992
Region	U.S.A
Scope	The requirements cover emergency-signaling devices for the hearing impaired, including strobes, vibrating alarms, and air-movement.
Notification technology requirements	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 60-120 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.

Table 34. Review of UL 217.

Type	Standard
Name	UL 217 "Standards for safety – smoke alarms" [54]
Edition	Ninth edition (January 2nd 2020) including revisions dated 28th of April 2021.
First issued	January 1976
Region	U.S.A
Scope	The requirements cover 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.
Notification technology requirements	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 meters distance for at least 4 minutes. 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.

Table 35. Review of UL 268 / ULC-S529.

Type	Standard
Name	UL 268 / ULC-S529 "Standards for safety – Smoke detectors for fire alarm systems" [55]
Edition	Seventh edition (January 11th 2016) including revisions dated 31st of October 2019.
First issued	N/A
Region	U.S.A / Canada
Scope	In contrast to UL 217, UL 268 covers smoke alarms that are part of a bigger fire alarm system.
Notification technology requirements	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 meters distance for at least 4 minutes. 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).

Table 36. Review of UL 464 / ULC-S525.

Type	Standard
Name	UL 464/ULC-S525 "Standards for safety - Audible Signaling Devices for Fire Alarm and Signaling Systems, Including Accessories" [56]
Edition	10th edition (January 28th 2016) including revisions dated 5th of September 2017.
First issued	N/A
Region	U.S.A /Canada
Scope	Applies to audible signaling devices for fire alarm and signaling systems.
Notification technology requirements	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 meters distance for at least 4 minutes. 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. 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).

Table 37. Review of ULC-S531.

Type	Standard
Name	ULC-S531 "Standard for smoke alarms" [57]
Edition	4th edition, (May 17th 2019)
First issued	November 1999
Region	Canada
Scope	The requirements cover 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.
Notification technology requirements	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 meters distance for at least 4 minutes. 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).

3.3. Survey responses

This section presents the key results from the survey. The full extent of the survey can be found in Appendix 2. The results are presented separately for people who were deaf or hard of hearing, support persons, and people working in the fire safety domain.

As stated, 75 people participated in the survey, of which 36 were people who were deaf or hard of hearing, 18 people who were support persons for people who are deaf or hard of hearing, and 21 people who worked in the domain of fire safety. Sixty-four of the respondents resided in the United States, and eleven 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.

3.3.1. Survey responses from people who were deaf or hard of hearing

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 of people who were deaf or hard of hearing is displayed in Figure 2.

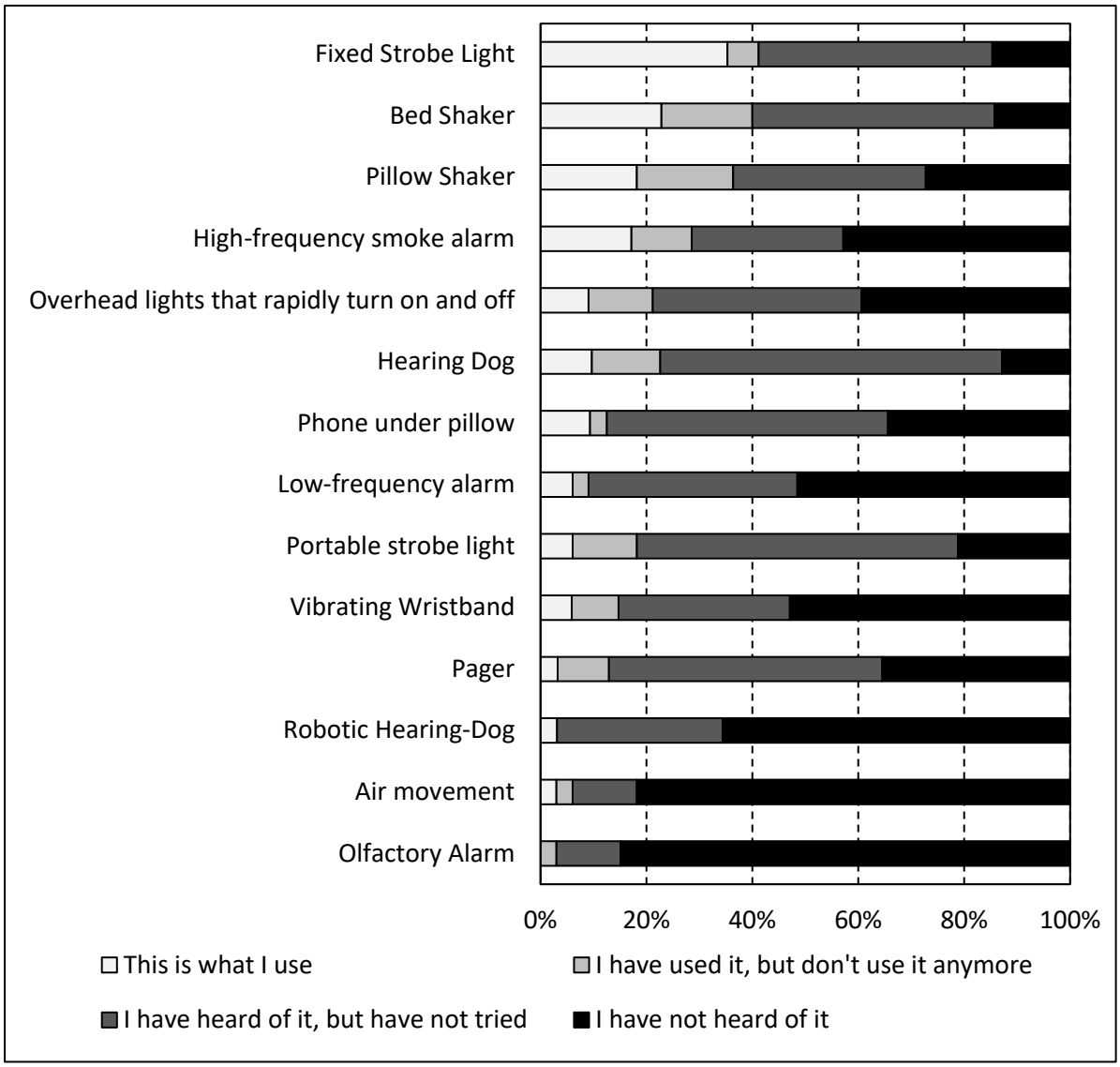

Figure 2. Experiences with different alarm technologies of people who were deaf or hard of hearing (N = 35).

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 from people who were deaf or hard of hearing is shown in Figure 3.

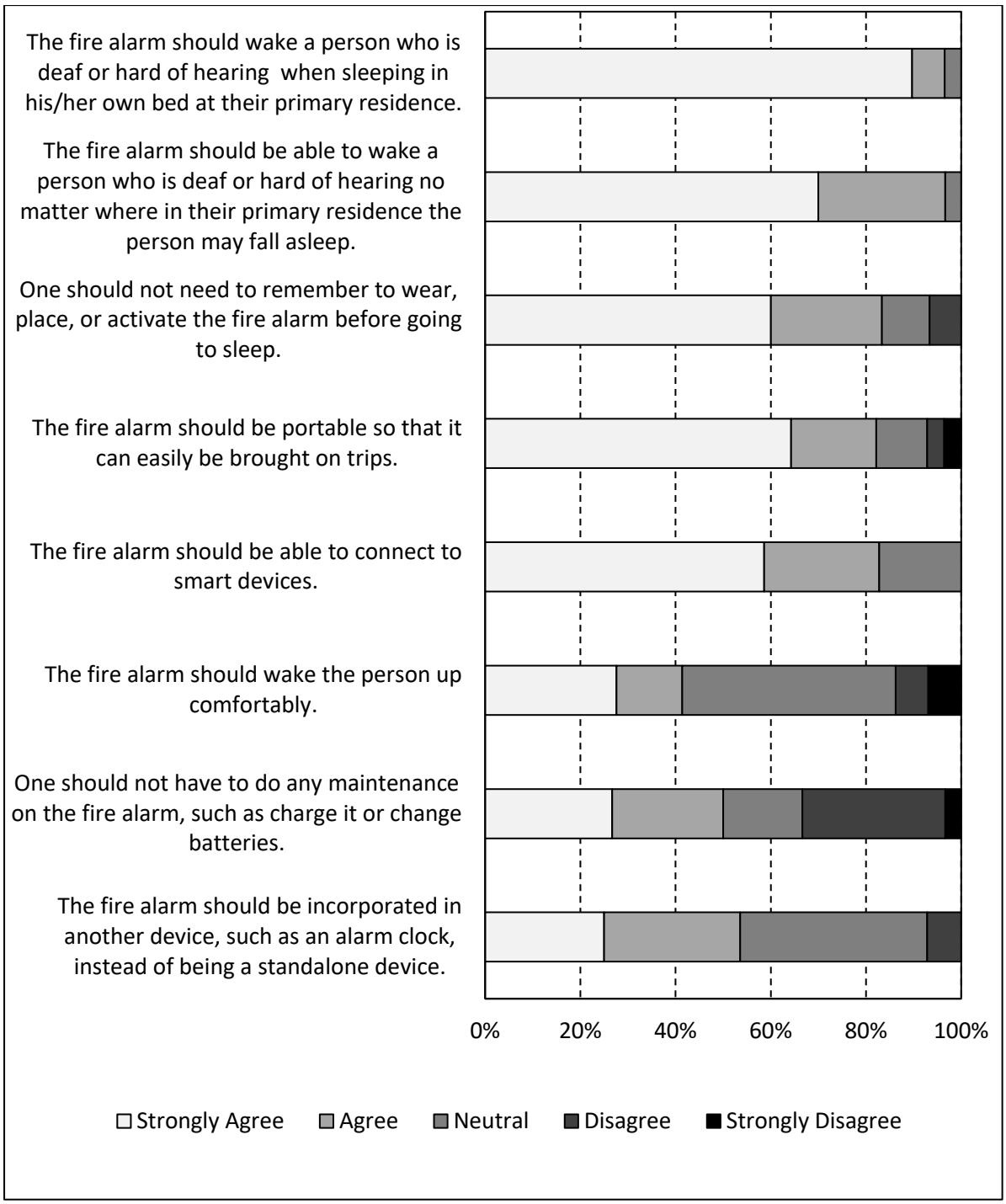

Figure 3. Preference of people who were deaf or hard of hearing when it comes to alarm characteristics in their primary residence (N = 30).

The survey respondents who were deaf or hard of hearing 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. The results are shown in Figure 4.

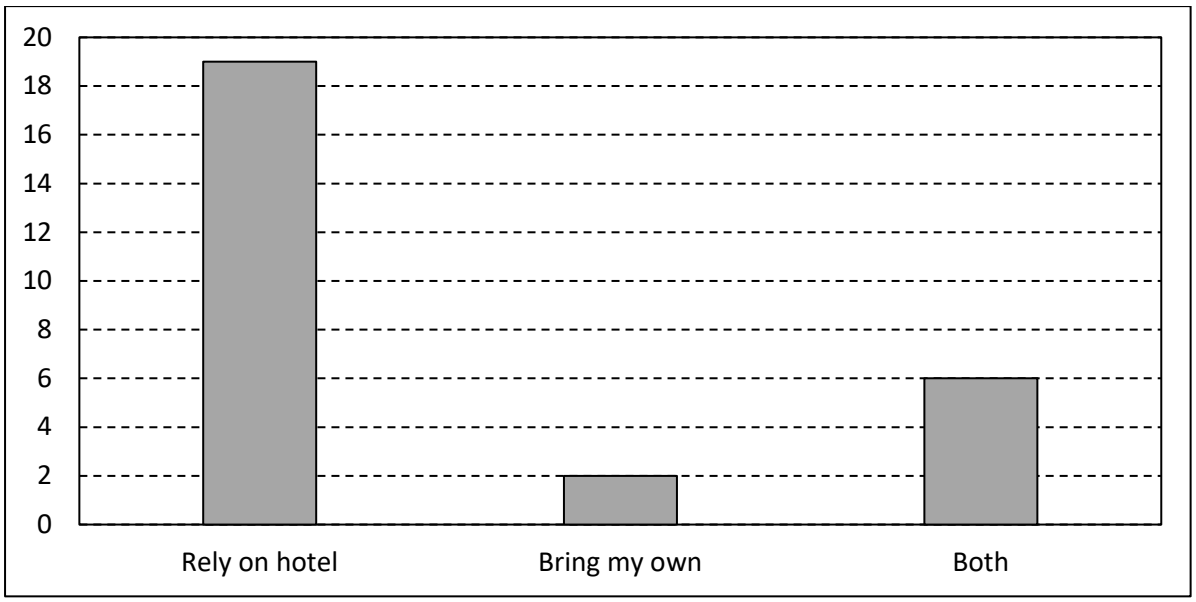

Figure 4. Experiences of people who were deaf or hard of hearing when it comes to the provision of alarm technologies in hotel and lodging establishments (N = 27).

Survey respondents who were deaf or hard of hearing were also asked about their references regarding various characteristics of alarm technologies, in relation to the setting of hotel or lodging establishments. The results are shown in Figure 5.

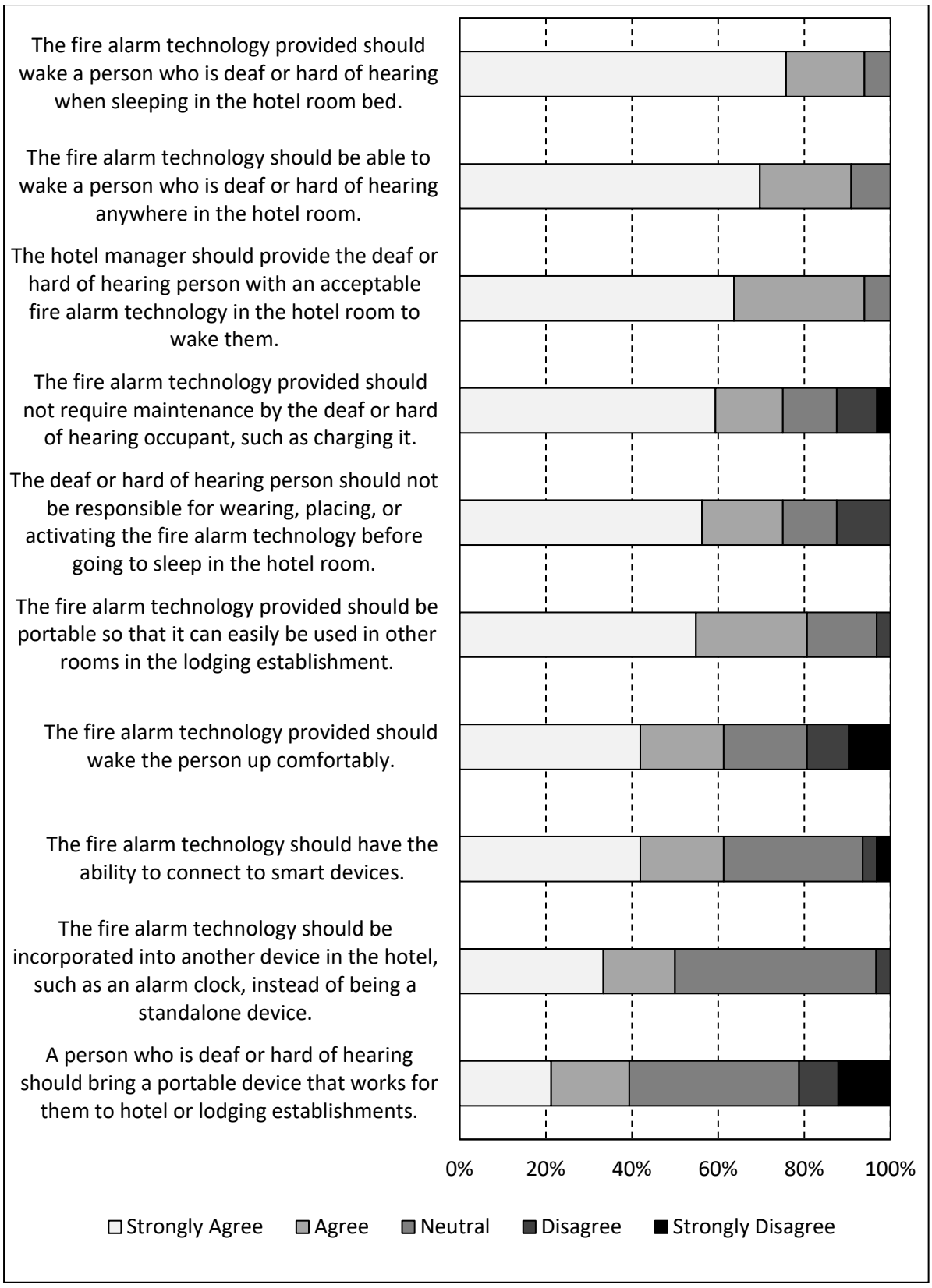

Figure 5. Preference of people who were deaf or hard of hearing when it comes to alarm characteristics when visiting hotel or lodging establishment (N = 33).

3.3.2. Survey responses from people who were support persons for people who are deaf or hard of hearing

The survey respondents were asked regarding their experience with various alarm technologies. The survey responses of people who were support persons to people who are deaf or hard of hearing is displayed in Figure 6.

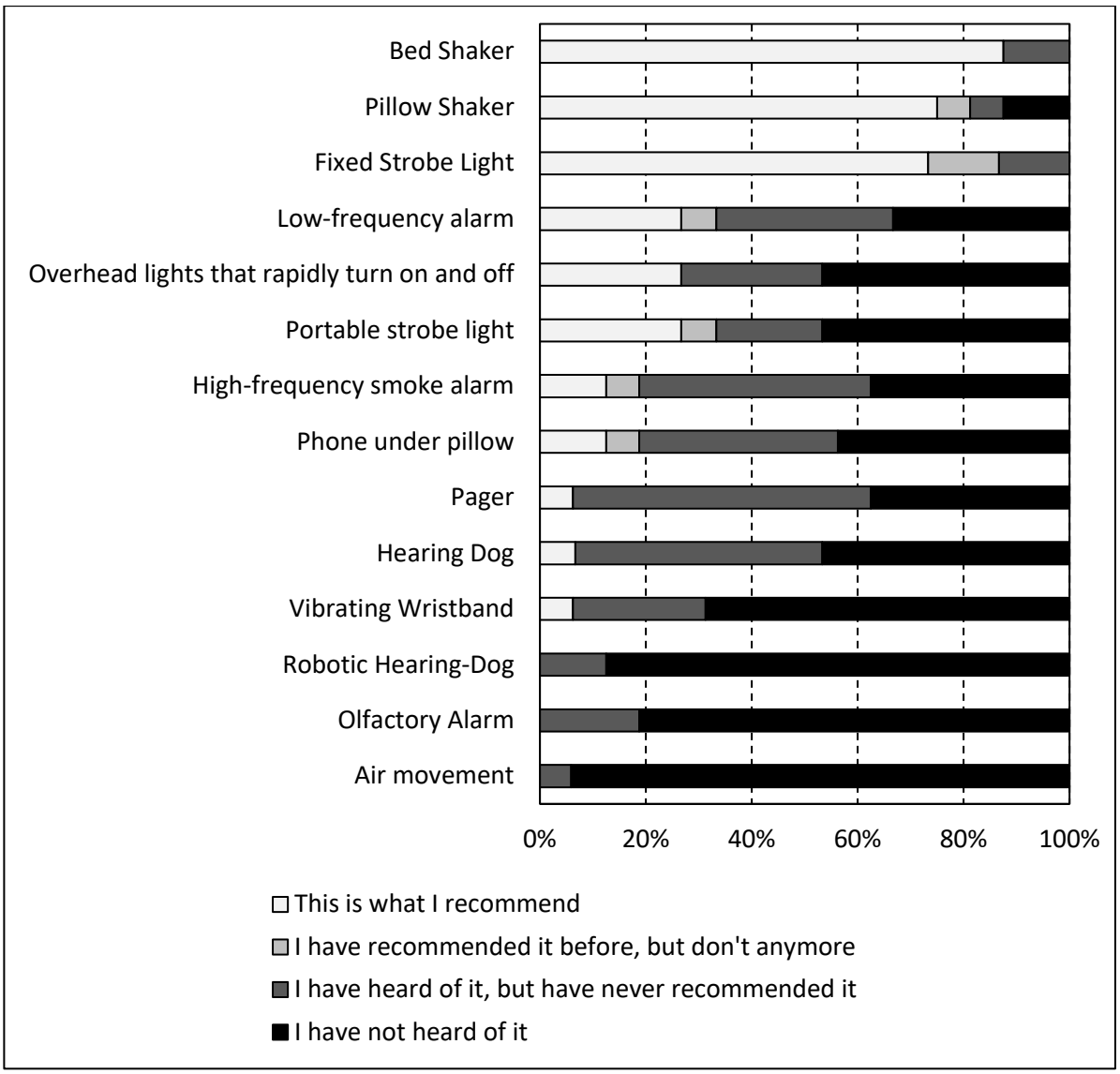

Figure 6. Experiences with different alarm technologies of people who were support persons to people who are deaf or hard of hearing (N = 17).

The survey respondents were also asked for their preference regarding various characteristics of fire alarm technologies, in the setting of the primary residence of people who are deaf or hard of hearing. The results from people who were support persons to people who are deaf or hard of hearing is shown in Figure 7.

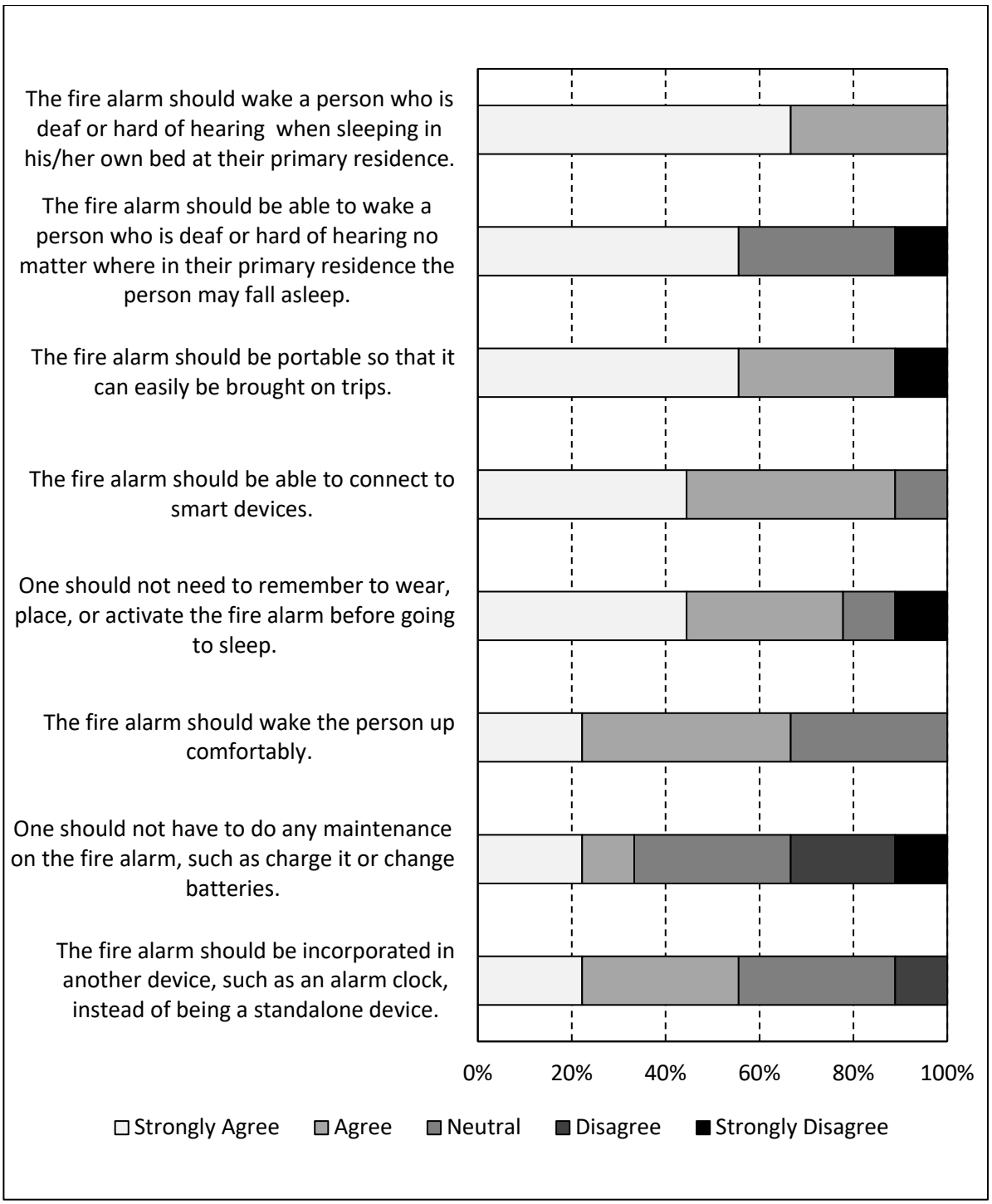

Figure 7. Preference of people who were support persons to people who are deaf or hard of hearing when it comes to alarm characteristics in their primary residence of people who are deaf or hard of hearing (N = 9).

Survey respondents who were support persons to people who are deaf or hard of hearing were also asked about their references regarding various characteristics of alarm technologies, in relation to the setting of hotel or lodging establishments. The results are shown in Figure 8.

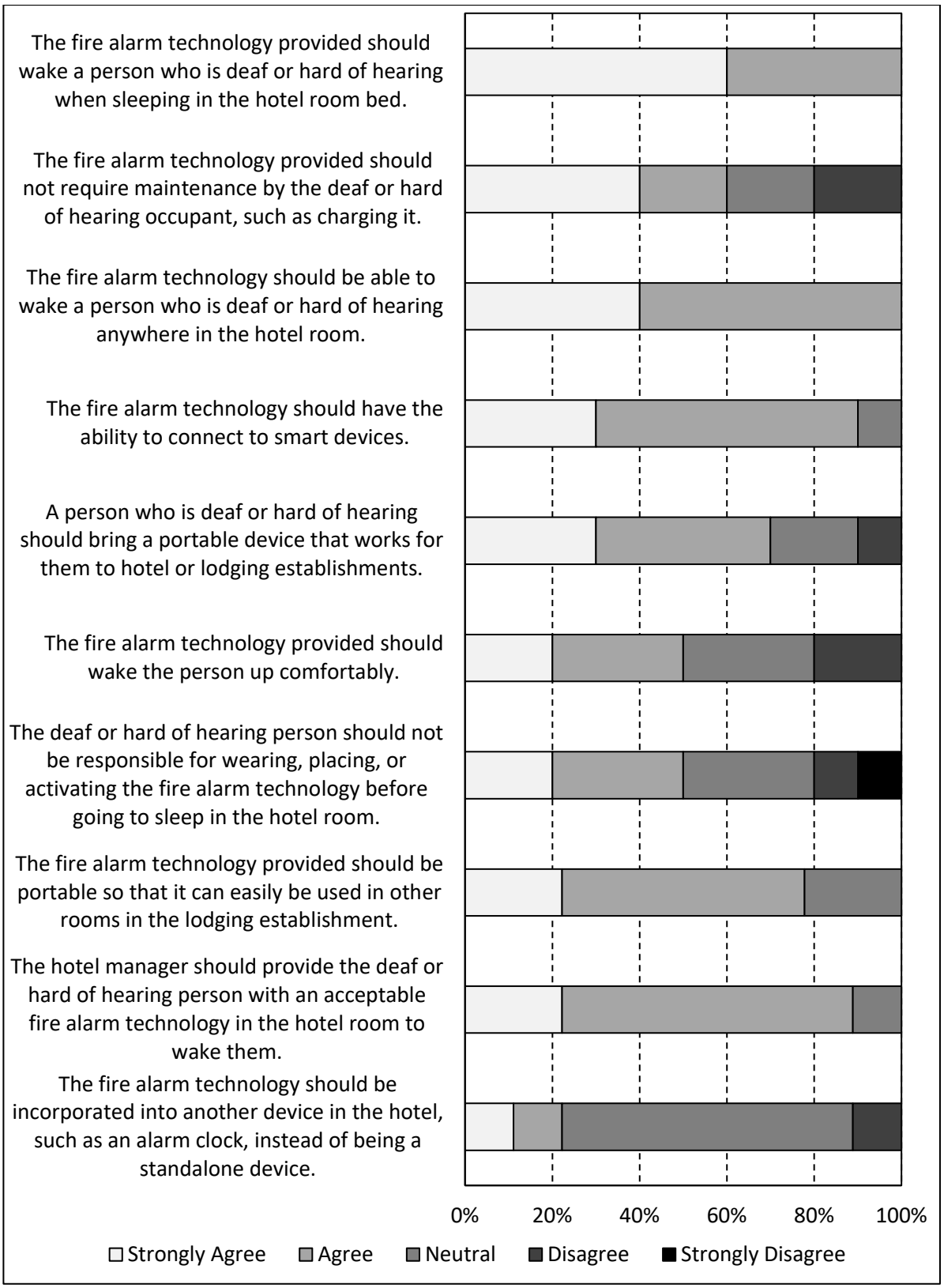

Figure 8. Preference of people who were support persons to people who are deaf or hard of hearing when it comes to alarm characteristics when visiting hotel or lodging establishment (N = 10).

3.3.3. Survey responses from people who worked in the domain of fire safety

The survey respondents were asked regarding their experience with various alarm technologies. The survey responses of people who worked in the domain of fire safety is displayed in Figure 9.

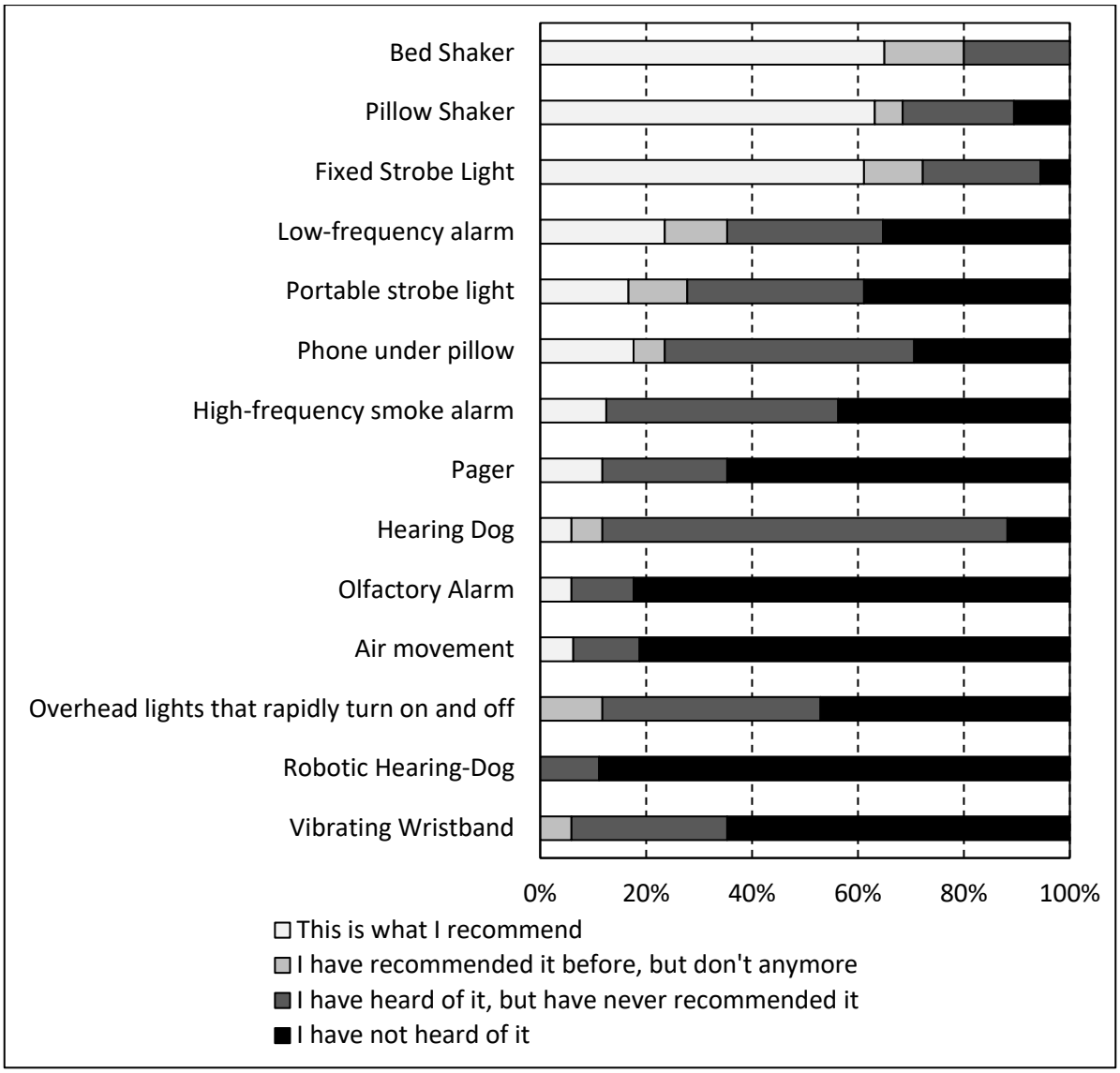

Figure 9. Experiences with different alarm technologies of people who worked in the domain of fire safety (N = 20).

The survey respondents were also asked for their preference regarding various characteristics of fire alarm technologies, in the setting of the primary residence of people who are deaf or hard of hearing. The results from people who were support persons to people who are deaf or hard of hearing is shown in Figure 10.

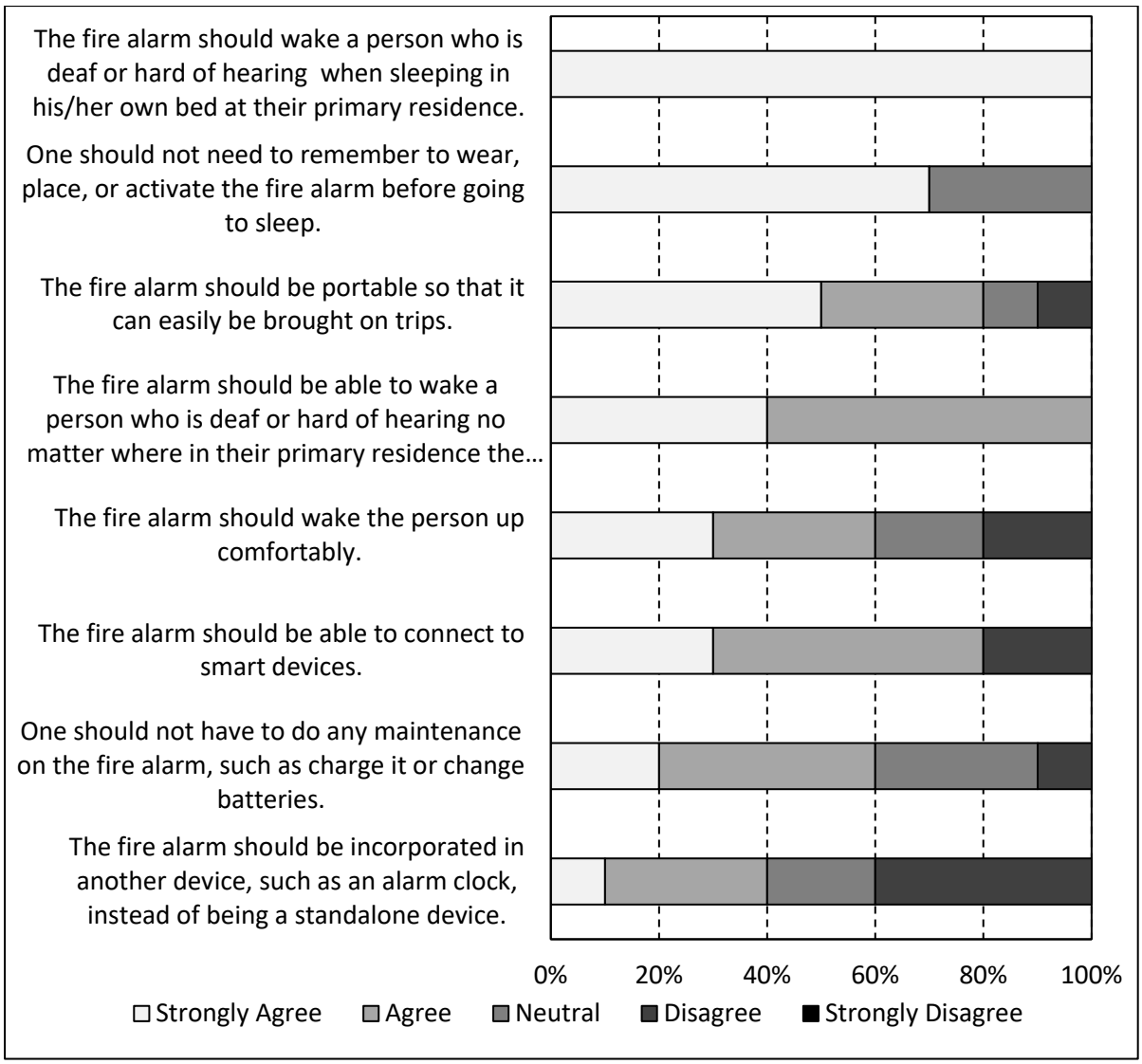

Figure 10. Preference of people who worked in the domain of fire safety when it comes to alarm characteristics in the primary residence of people who are deaf or hard of hearing (N = 10).

Survey respondents who were support persons to people who are deaf or hard of hearing were also asked about their references regarding various characteristics of alarm technologies, in relation to the setting of hotel or lodging establishments. The results are shown in Figure 11.

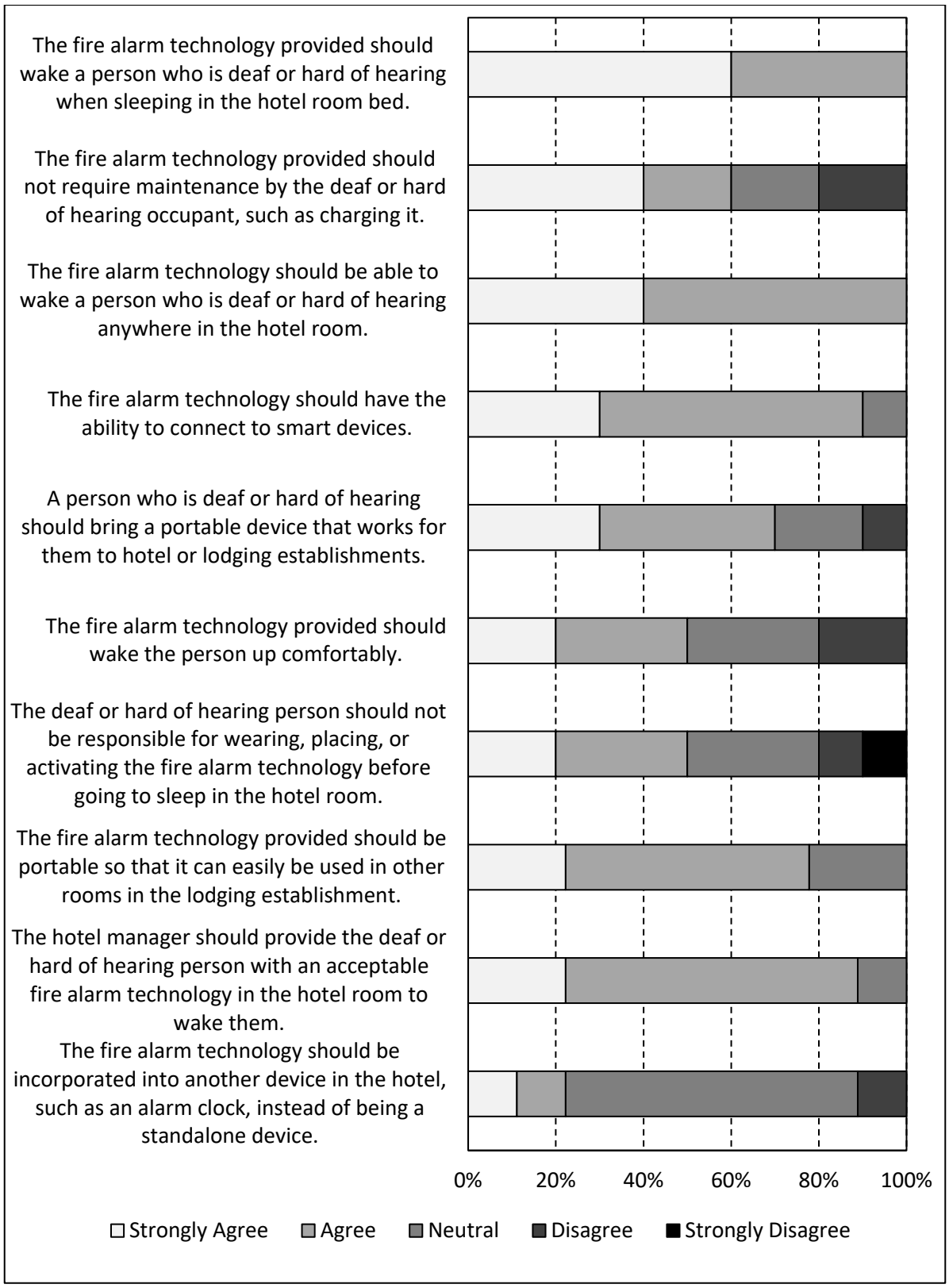

Figure 11. Preference of people who worked in the domain of fire safety when it comes to alarm characteristics when visiting hotel or lodging establishment (N = 14).

4. Discussion

From the review, it can be seen that some technologies have been investigated to a wider extent from both the scientific community as well as manufacturers. These technologies include audible alarms (both high-frequency and low-frequency), strobe lights, and bed and pillow shakers. Table 38 summarizes the findings from this review. It should be noted that this is based on the subjective assessment of the authors based on the available literature reported in section 3.1, and findings should be considered indicative rather than definitive. The evaluations consider both people who are hard of hearing and people who are deaf.

Table 38. Summary of technologies and their respective suggested effectiveness and strength of evidence, based on the subjective assessment of the authors.

Technologies	Suggested relative effectiveness	Relative strength of evidence	Field of application
High-frequency alarm	Medium	Very strong	Not suitable for deaf
Low-frequency alarm	High	Very strong	Less suitable for deaf
Olfactory alarm	Low	Medium	Maybe less suitable for males
Air movement	Medium	Low	Maybe less suitable for children
Bed shaker	High	Medium	Maybe less suitable for elderly
Electric shocks	N/A	Very low	Not applicable as notification technology due to ethical reasons
Hearing-dog robot	High	Low	-
Heater	Low	Very low	Not applicable as notification technology due to slow reaction time
Pager	Low	Very low	-
Phone under pillow	High	Very low	-
Pillow shaker	High	Medium	Maybe less suitable for elderly
Vibrating wristband	Medium	Very low	-
Strobes	Low	Strong	-

Based on the findings from the literature review, it is suggested that the high frequency-smoke alarm is inefficient in awakening people who are deaf and hard of hearing, among many others vulnerable groups [33]. The low-frequency smoke alarm is significantly more effective for people who are hard of hearing, but still ineffective for people who are deaf [11]–[13]. 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 [12], [13], [17]–[19]. 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 [12]. Important to note is that in older age groups, the prevalence of hearing loss is higher [9]. Another limiting factor is that there is no satisfactory standardized way of measuring the vibrational capabilities of these devices, making it more difficult to standardize them. This has been recognized by other researchers as well [12]. It is also argued that such a standardized measurement would facilitate research into their effectiveness.

Much of the data of awakening of sleeping people who are deaf or hard of hearing are based on data from younger people. However, the sleeping patterns of a young and old individual are not the same [59], and people who are older may be more likely to awake due to the decrease in slow-wave sleep [60]. This is in contrast with the findings reported by Bruck and Thomas [12] regarding the effectiveness of bed shakers

and pillow shakers. This issue deserves further research, as hearing loss is more prevalent in the older population [9].

Although many of the studies included in this review report on thresholds for awakening, these numbers should be treated with most caution. In all of the above studies, the participants have been aware of the nature of the experiments, and the meaningfulness of the presented signals is therefore different from what it would be in a real case. Previous research has shown that priming (i.e. altering the meaningfulness of the signal) increased the likelihood of waking up from 25% to 90% [61]. It is also fair to assume that how the priming is conducted has an effect of the perceived signal meaningfulness. Therefore, the reported thresholds should not be seen as reliable indicators of how people would react in real life. Instead, the thresholds might be used to rank the effectiveness of different alarm technologies within a study. This also highlights why it is important with numerous studies investigating the same technology.

Evidence suggests that people may be more or less sensitive to different kinds of stimuli [12]. This is also supported by the vast individual differences reported in the different studies. This highlights that solutions potentially working for some people might not work for others, and that the choice of alarm technology therefore should be decided on an individual level whenever appropriate.

One important future endeavor is to develop a usable standard for bed and pillow shakers and other tactile alarm technologies. As of today (and as of 2007 [12]), there are few standard available. One of those is BS 5446-3:2015 [43]. However, this standard has been shown to be expensive and difficult to comply with [12]. The standard BS 5446-3:2015 [43] included in this review is the second edition of the standard. It is possible that the requirements have been improved from the first edition, but this cannot be asserted, as the first edition of the standard was not obtained in this study. Another standard identified that specified vibrational requirements for bed and pillow shakers was UL 1971, third edition [53]. However, the standard contained no details on how the vibrational strength should be measured, other than that is should have a radial displacement of at least 1/8 inch (3.2 mm). A useful standard should be placement-independent if possible. In other words, it should be possible to use the standard for a variety of different vibration technologies. Research on appropriate vibration levels needs to be conducted. The research studies covered in this report provide valuable information, but unfortunately, it is not possible to identify how much vibration the sleeping participants perceived. This information is crucial in order to develop a usable and reliable standard and require further studies.

It is recommended that future empirical research on the effectiveness of bed shakers or pillow shakers make use of a 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 mattress or under pillow) remains unsolved. Experimental research investigating how vibrations transmit when installed in different configurations/locations in a bed is therefore deemed necessary. By classifying the technologies according to their performance in providing the user with tactile feedback, rather than their vibrational capabilities in an artificial setting, manufacturers could be encouraged to be more creative, and research into the subject would be facilitated.

The results from the survey provided in section 3.3 provide valuable insight into the experiences and preferences of people who are deaf or hard of hearing, and other relevant stakeholders, 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. 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 (Figure 2). This is in line with the provision of these alarms on the market, as well as the recommendations of both support persons and people working within the domain of fire safety, as can be seen in figures 6 and 9. The low-frequency alarm seems to be largely unknown in the community despite its proven efficiency. This might indicate that more efforts need to be done towards promoting this kind of alarm technology to the community. Interesting to note is that support persons and

people working in the domain of fire safety seem to have more experience with low-frequency audible alarms than people who were deaf or hard of hearing. It should also be noted that strobe lights were commonly recommended by support persons and fire safety experts, despite the inefficiency reported in the scientific literature.

The preferences related to alarm technologies were similar irrespective of context (residence or hotel/lodging establishment) and stakeholders. 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. 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. This could be interpreted as the community's preference of having an alarm that has similar characteristics as the regular audible smoke alarm. These preferences can be addressed only by some 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. Therefore, it does not fulfil the preference of waking people irrespective of where they happen to fall asleep. The strobe light might be regarded as the technologies most similar to the regular audible smoke alarm in terms of characteristics, but the literature ([11]–[13], [18], [19]) suggests that it is not efficient in terms of awakening sleeping people who are deaf or hard of hearing from deeper stages of sleep. The experiences of individuals should be taken into account when identifying the most suitable technologies to be used for a given purpose. From Figure 2 it can be seen that fixed strobe lights are commonly used, maybe implying that the respondents using them consider them to be reliant. It is not known from the results of the survey if the respondents only had the alarm technologies installed, or if they also had tested them while 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. It is unclear why this is the case, but this seems to provide a clear indication of the need for establishments to address this issue themselves. While both people who were deaf or hard of hearing, and support persons agreed on the fact that the manager should provide you with an alarm technology, the people working in the domain of fire safety agreed more with the statement that people who are deaf or hard of hearing should bring their own alarm (Figures 5, 6 and 11). The survey responses do not provide any clear information as to why this is the case. One possible explanation could be that the people working in the domain of fire safety answered the question considering the situation as it is today, while people who were deaf or hard of hearing answered the question projecting an ideal scenario.

Recent advances in mobile and internet technology have not been investigated from a fire safety point of view. Today, modern smartphones may have a set of features which would be very useful for technologies concerning the alerting of people that are deaf or hard of hearing (e.g., advanced sound recognition, interconnected wearable devices, etc.). Those features are deemed to provide additional opportunities for fire safety purposes in the not so distant future.

5. Conclusion

Based on the scientific literature found in this scoping review, it is deemed necessary to re-evaluate the recommendation of strobes as an alternative alarm technology for awakening people who are deaf or hard of hearing. The literature concludes 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. 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. The survey also indicates

that support persons and fire safety experts may recommend technologies that have been proven ineffective in the scientific literature. It is therefore argued that information campaigns are needed towards these target groups. It is also argued that efforts are aimed towards developing a usable standard for alarm technologies incorporating tactile signals. New technologies, such as wearable devices, should be further investigated to establish their effectiveness in waking up people who are deaf or hard of hearing.

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Appendix 1 – Search strings used

Search string used for PsycInfo (search date: 2021-01-14):

((awake OR wake* OR asleep* OR sleep*) AND (fire* OR evacuat* OR alarm* OR alert*) AND (deaf* OR "hearing loss*" OR "hearing impair*" OR "hard of hearing" OR "impaired hearing" OR "hearing-impair*" OR "hard-of-hearing" OR "unhearing" OR "without hearing"))*

Search string used for PubMed (search date: 2021-01-14):

((awake OR wake* OR asleep* OR sleep*) AND (fire* OR evacuat* OR alarm* OR alert*)) AND (deaf* OR "hearing loss*" OR "hearing impair*" OR "hard of hearing" OR "impaired hearing" OR "hearing-impair*" OR "hard-of-hearing" OR "unhearing" OR "without hearing")*

Search string used for Scopus (search date: 2021-01-14):

TITLE-ABS-KEY ((awake OR wake* OR asleep* OR sleep*) AND (fire* OR evacuat* OR alarm* OR alert*) AND (deaf* OR "hearing loss*" OR "hearing impair*" OR "hard of hearing" OR "impaired hearing" OR "hearing-impair*" OR "hard-of-hearing" OR "unhearing" OR "without hearing"))*

Search string used for Web of Science (search date: 2021-01-14):

ALL=((awake OR wake* OR asleep* OR sleep*) AND (fire* OR evacuat* OR alarm* OR alert*) AND (deaf* OR "hearing loss*" OR "hearing impair*" OR "hard of hearing" OR "impaired hearing" OR "hearing-impair*" OR "hard-of-hearing" OR "unhearing" OR "without hearing"))*

Search string used for Google Scholar (search date: 2021-01-14):

allintitle:(deaf OR "hard of hearing" OR "hearing impaired" OR "hearing impairment" OR "hearing loss" OR "hearing aid")((alarm OR alarms OR alert OR notification OR notifying OR alerting) OR (awake OR wake OR waking OR awaking OR sleeping))

Search string used for NFPA Database (search date: 2021-01-14):

*alarm**
*waking**

Appendix 2 – Survey questions

The survey consists of 18 different questions. However, no person answers all questions. The logic of the survey is explained in square brackets after each answer option or question, whichever is applicable.

Q1: Where do you live? [Go to Q2]

- □ Inside the United States.
- □ Outside the United States (please specify the country).

Q2: I am a:

- □ Person who is deaf or hard of hearing. [Go to Q3]
- □ Parent of a person who is deaf or hard of hearing. [Go to Q5]
- □ Educator of a person who is deaf or hard of hearing. [Go to Q5]
- □ Service provider/accessibility coordinator for people who are deaf or hard of hearing. [Go to Q5]
- □ Other – Person who identifies as more than one of these: Please specify in the comment field below. [Go to Q3]
- □ Other – Person who does not identify with any of these. Please specify in comment field below. [Go to Q5]

Q3: What experiences have you had with the following fire alarm technologies? [Go to Q4]

	This is what I use	I have used it, but don't use it anymore	I have heard of it, but have not tried	I have not heard of it
Air movement (e.g. fans or similar)	□	□	□	□
Olfactory Alarm	□	□	□	□
Vibrating Wristband	□	□	□	□
Phone under pillow	□	□	□	□
Hearing Dog	□	□	□	□
Robotic Hearing-Dog	□	□	□	□
Pager	□	□	□	□
Fixed Strobe Light (e.g. strobe on a fire alarm sounder)	□	□	□	□
Portable strobe light	□	□	□	□
Overhead lights that rapidly turn on and off	□	□	□	□
High-frequency smoke alarm (high pitch consistent sound that is abrasive)	□	□	□	□
Low-frequency alarm (low pitch tonal sound that can be abrasive over long periods of exposure)	□	□	□	□
Bed Shaker	□	□	□	□
Pillow Shaker	□	□	□	□

Q4: Do you own or rent your home?

- □ Own [Go to Q7]
- □ Rent [Go to Q11]
- □ Not applicable [Go to Q16]

Q5: As a caretaker, educator, service provider or other person assisting someone who is deaf or hard of hearing, what experiences have you had with the following fire alarm technologies? [Go to Q6]

	This is what I recommend	I have recommended it before, but don't anymore	I have heard of it, but never recommended it	I have not heard of it
Air movement (e.g. fans or similar)	□	□	□	□
Olfactory Alarm	□	□	□	□
Vibrating Wristband	□	□	□	□
Phone under pillow	□	□	□	□
Hearing Dog	□	□	□	□
Robotic Hearing-Dog	□	□	□	□
Pager	□	□	□	□
Fixed Strobe Light (e.g. strobe on a fire alarm sounder)	□	□	□	□
Portable strobe light	□	□	□	□
Overhead lights that rapidly turn on and off	□	□	□	□
High-frequency smoke alarm (high pitch consistent sound that is abrasive)	□	□	□	□
Low-frequency alarm (low pitch tonal sound that can be abrasive over long periods of exposure)	□	□	□	□
Bed Shaker	□	□	□	□
Pillow Shaker	□	□	□	□

Q6: Do you own or rent your home?

- □ Own [Go to Q7]
- □ Rent [Go to Q11]
- □ Not applicable [Go to Q16]

Q7: In your primary residence, how well do you agree with the following statements about the functionality of fire alarm technologies for those who are deaf or hard of hearing? [Go to Q8]

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	N/A
The fire alarm should wake a person who is deaf or hard of hearing when sleeping in his/her own bed at their primary residence.	□	□	□	□	□	□
The fire alarm should be portable so that it can easily be brought on trips.	□	□	□	□	□	□
The fire alarm should be able to wake a person who is deaf or hard of hearing no matter where in their primary residence the person may fall asleep.	□	□	□	□	□	□
The fire alarm should be incorporated in another device, such as an alarm clock, instead of being a standalone device.	□	□	□	□	□	□
One should not need to remember to wear, place, or activate the fire alarm before going to sleep.	□	□	□	□	□	□
One should not have to do any maintenance on the fire alarm, such as charge it or change batteries.	□	□	□	□	□	□
The fire alarm should be able to connect to smart devices.	□	□	□	□	□	□
The fire alarm should wake the person up comfortably.	□	□	□	□	□	□

Q8: When you go to a hotel or lodging establishment, do you bring your own alarm technology or do you rely on the hotel to provide one for you? [Go to Q9]

- □ Bring my own
- □ Rely on hotel
- □ Both
- □ Other (please specify)

Q9: When you go to a hotel or lodging establishment as someone who is or with someone who is deaf or hard of hearing, how well do you agree with the following statements? [Go to Q10]

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	N/A
The hotel manager should provide the deaf or hard of hearing person with an acceptable fire alarm technology in the hotel room to wake them.	□	□	□	□	□	□
A person who is deaf or hard of hearing should bring a portable device that works for them to hotel or lodging establishments.	□	□	□	□	□	□
The fire alarm technology provided should wake a person who is deaf or hard of hearing when sleeping in the hotel room bed.	□	□	□	□	□	□
The fire alarm technology provided should be portable so that it can easily be used in other rooms in the lodging establishment.	□	□	□	□	□	□
The fire alarm technology should be able to wake a person who is deaf or hard of hearing anywhere in the hotel room.	□	□	□	□	□	□
The fire alarm technology should be incorporated into another device in the hotel, such as an alarm clock, instead of being a standalone device.	□	□	□	□	□	□
The deaf or hard of hearing person should not be responsible for wearing, placing, or activating the fire alarm technology before going to sleep in the hotel room.	□	□	□	□	□	□
The fire alarm technology provided should not require maintenance by the deaf or hard of hearing occupant, such as charging it.	□	□	□	□	□	□
The fire alarm technology should have the ability to connect to smart devices.	□	□	□	□	□	□
The fire alarm technology provided should wake the person up comfortably.	□	□	□	□	□	□

Q10: Please provide a description of any technologies that you are currently using or that you have found helpful for waking. (free-text answers) [End of survey]

Q11: Has your property manager provided you with any supplemental fire alarm technologies that work with the building's fire alarm systems? [Go to Q12]

- □ Yes
- □ No

Q12: In your primary residence, how well do you agree with the following statements about the functionality of fire alarm technologies for those who are deaf or hard of hearing? [Go to Q13]

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	N/A
The fire alarm technology should wake a person who is deaf or hard of hearing when sleeping in his/her own bed at their primary residence.	□	□	□	□	□	□
The fire alarm technology should be portable so that it can be used in other rooms.	□	□	□	□	□	□
The fire alarm technology should be able to wake a person who is deaf or hard of hearing regardless of its location.	□	□	□	□	□	□
The fire alarm should be incorporated in another device, such as an alarm clock, instead of being a standalone device.	□	□	□	□	□	□
The deaf or hard of hearing person should not be responsible for wearing, placing, or activating the fire alarm technology before going to sleep.	□	□	□	□	□	□
The fire alarm technology should not require maintenance, such as charging it or changing batteries.	□	□	□	□	□	□
The fire alarm technology should have the ability to connect to smart devices.	□	□	□	□	□	□
The fire alarm should wake the person up comfortably.	□	□	□	□	□	□

Q13: When you go to a hotel or lodging establishment, do you bring your own alarm technology or do you rely on the hotel to provide one for you? [Go to Q14]

- □ Bring my own
- □ Rely on hotel
- □ Both
- □ Other (please specify)

Q14: When you go to a hotel or lodging establishment as someone who is or with someone who is deaf or hard of hearing, how well do you agree with the following statements? [Go to Q15]

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	N/A
The hotel manager should provide the deaf or hard of hearing person with an acceptable fire alarm technology in the hotel room to wake them.	□	□	□	□	□	□
A person who is deaf or hard of hearing should bring a portable device that works for them to hotel or lodging establishments.	□	□	□	□	□	□
The fire alarm technology provided should wake a person who is deaf or hard of hearing when sleeping in the hotel room bed.	□	□	□	□	□	□
The fire alarm technology provided should be portable so that it can easily be used in other rooms in the lodging establishment.	□	□	□	□	□	□
The fire alarm technology should be able to wake a person who is deaf or hard of hearing anywhere in the hotel room.	□	□	□	□	□	□
The fire alarm technology should be incorporated into another device in the hotel, such as an alarm clock, instead of being a standalone device.	□	□	□	□	□	□
The deaf or hard of hearing person should not be responsible for wearing, placing, or activating the fire alarm technology before going to sleep in the hotel room.	□	□	□	□	□	□
The fire alarm technology provided should not require maintenance by the deaf or hard of hearing occupant, such as charging it.	□	□	□	□	□	□
The fire alarm technology should have the ability to connect to smart devices.	□	□	□	□	□	□
The fire alarm technology provided should wake the person up comfortably.	□	□	□	□	□	□

Q15: Please provide a description of any technologies that you are currently using or that you have found helpful for waking. (free-text answers) [End of survey]

Q16: When you go to a hotel or lodging establishment, do you bring your own alarm technology or do you rely on the hotel to provide one for you? [Go to Q17]

- □ Bring my own
- □ Rely on hotel
- □ Both

□ Other (please specify)

Q17: When you go to a hotel or lodging establishment as someone who is or with someone who is deaf or hard of hearing, how well do you agree with the following statements? [Go to Q18]

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	N/A
The hotel manager should provide the deaf or hard of hearing person with an acceptable fire alarm technology in the hotel room to wake them.	□	□	□	□	□	□
A person who is deaf or hard of hearing should bring a portable device that works for them to hotel or lodging establishments.	□	□	□	□	□	□
The fire alarm technology provided should wake a person who is deaf or hard of hearing when sleeping in the hotel room bed.	□	□	□	□	□	□
The fire alarm technology provided should be portable so that it can easily be used in other rooms in the lodging establishment.	□	□	□	□	□	□
The fire alarm technology should be able to wake a person who is deaf or hard of hearing anywhere in the hotel room.	□	□	□	□	□	□
The fire alarm technology should be incorporated into another device in the hotel, such as an alarm clock, instead of being a standalone device.	□	□	□	□	□	□
The deaf or hard of hearing person should not be responsible for wearing, placing, or activating the fire alarm technology before going to sleep in the hotel room.	□	□	□	□	□	□
The fire alarm technology provided should not require maintenance by the deaf or hard of hearing occupant, such as charging it.	□	□	□	□	□	□
The fire alarm technology should have the ability to connect to smart devices.	□	□	□	□	□	□
The fire alarm technology provided should wake the person up comfortably.	□	□	□	□	□	□

Q18: Please provide a description of any technologies that you are currently using or that you have found helpful for waking. (free-text answers) [End of survey]