Chapter 8
Smoke Alarms and the Human Response

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Abstract Smoke alarms are mandated in all man-made structures designed for human occupancy in most developed nations, and as such, they have become a normal and expected feature of our environment. Most people understand that their purpose is to alert building occupants to the possibility of fire. Despite this, it is wrong to assume that when a smoke alarm sounds the human response will be uniformly predictable. There are many different factors influencing whether or not a person will respond to an alarm, and these vary depending upon whether a person is awake or asleep, and audibility factors within the environment. This chapter will begin with a brief history of smoke alarm use and design and then proceed to a review of recent literature on human response to the smoke alarm signal when people are asleep, and when they are awake.

Keywords Smoke alarms · Human response · Auditory arousal · Cognitive processing during sleep · Alarm signal characteristics

1 Smoke Alarms

1.1 Brief History

Despite their pervasive presence in modern structures, smoke alarms have a relatively brief history compared to other fundamental inventions of modern engineering and architecture. Smoke alarms were not widely used in residential settings until events following Hurricane Agnes in 1971 pointed to their effectiveness. As a part of their disaster relief effort, the US Department of Housing and Urban Development

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purchased 17 000 mobile homes and requested that the National Bureau of Standards (NSB; later to be known as NIST) implement high standard fire safety systems [19]. Consequently, single station smoke alarms were installed outside the bedrooms of each unit. In the ensuing years after the homes were inhabited, the statistically predicted number of fires still occurred, but zero deaths and very few injuries were recorded. From this stunning change in outcomes, it was surmised that smoke alarms were an effective means of alerting occupants to the presence of fire before they could become trapped, and the US mobile housing industry adopted the first smoke alarm regulation, decreeing that one smoke alarm was to be installed outside the bedrooms of every mobile home produced [19].

The mandating of smoke alarms in mobile homes precipitated the NSB to more closely examine their effectiveness, and work commenced to develop standards regarding the optimal number and placement of smoke alarms in residential homes. The Indiana Dunes tests were conducted, involving full scale testing of commercially available smoke alarms that were purposefully installed in homes prior to set demolishment [19]. Over a period of 2 years, 76 separate experiments were conducted using three different homes and involving the burning of real furnishings in varied conditions (e.g., doors/windows open or closed). Results of these experiments led to the conclusion that for optimum safety, smoke alarms should be located on each floor of a home [19]. This recommendation was adopted and laws were enacted across various jurisdictions in the US that required the installation of smoke alarms on each floor in new residential housing. From these promising beginnings, progress was slow. Internationally, laws regarding smoke alarm installation and placement have gradually been implemented, but it took many nations until the first decade of the 2000s for smoke alarms to be made compulsory in residences.

It is important to note that while the reduction in fire deaths following the advancements in smoke alarm legislation is clear, several other coinciding factors may also have lowered the incidence of injury and death. For example, advancements in the engineering of building materials, household furniture and items, and sleeping garments have afforded increased fire protection. Nonetheless, evidence indicates that smoke alarms are a vital component to improved fire safety systems.

Contemporary data continue to support the effectiveness of smoke alarms in the reduction of risk of death in residential fires. When considering the impact of smoke alarms, it is convenient to consider US statistics because the size of the population lends a robustness to the data. US data on home structure fires that were reported to local fire departments spanning the years from 2014 to 2018 indicated that the risk of dying in a home structure fire was 55% lower in homes where there was a working smoke alarm, compared to homes with no smoke alarms present, or none that operated [1]. The power source and method of extinguishment also seem to be important. When automatic extinguishing systems were not present, the death rate per 1000 fires was 35% lower when battery powered smoke alarms were present, 69% lower when the smoke alarms were hard-wired, and 51% lower when smoke alarms with either source of power were present. This climbed to 91%, lower when hard-wired smoke alarms were present with sprinklers [1]. A 2016 meta-analysis using data from US and Australian studies examining the association between smoke alarm presence and injury and death rates reported that the presence of a working smoke alarm halved the death rate in residential fires, but that there was no significant reduction in injuries due to their presence [58].

1.2 Smoke Alarm Types

A smoke alarm consists of two basic components within a single unit, including a smoke detector and an alarm sounding device (signal). Specifications for smoke alarms are generally mandated by local standards. These standards generally dictate aspects of both the detector and the alarm signal that are designed to increase the chance that occupants will be warned of a fire in time to evacuate or extinguish the fire while it is small, thereby decreasing the chance of damage to property, injury, and /or death of occupants. The detector should be designed to be sensitive to small levels of smoke, but at the same time not too sensitive to non-fire-related phenomena in an effort to reduce false alarms, which may cause undesirable behaviors such as the ignoring or disabling of alarms [69].

Smoke alarms vary in how they detect smoke, and how they are powered. New one or two family dwellings across many countries are now required to include smoke alarm units that are hard-wired into the main electricity supply by a professional electrician. These hard-wired units also include a 9 Volt (V) back–up battery in case of power failure. In older dwellings, and by far the most common type of smoke detector, is the independently operating battery powered unit. These devices are installed locally, without the need for professional services, and can be powered by a 9V battery that needs yearly replacement, or by a longer lasting lithium battery (approx. 10 year life). Regardless of power source, both manufacturers and fire services recommended that all smoke alarm units need to be replaced every 10 years to ensure optimal performance. Fire services commonly run public service campaigns to prompt correct maintenance of smoke alarms.

Individual smoke alarms can also be interconnected. Interconnection is an important safety feature that is recommended so that if smoke is detected in the area of one device, they all sound together, thereby increasing the possibility of alerting occupants who may be remote from the smoke alarm closest to the area of fire ignition [49]. Interconnection is mandated in some countries. For example, it has been mandated for new dwellings in the USA since 1989 (NFPA 72; [51]), and in Australia since 2014 [3]. Recently, Scottish legislation in relation to smoke alarms has been updated and has extended the requirement for interconnection to all existing dwellings by 2022 [59].

There are two primary types of detector that are typically used in either hard-wired or battery-operated smoke alarm units, including ionization and photoelectric. Smoke alarms are also available that include dual sensors, with one of each type. The two types of detector sense the presence of smoke differently, varying in their response to the visible and invisible properties of smoke [50]. An ionization type of alarm contains a small amount of the radioactive material, Americum-241, situated between two electrically charged plates. The Americum-241 ionizes the air between these plates, causing an electrical current to flow between them. The alarm is activated when smoke enters the chamber of the detector, disrupting the current between the plates. In contrast, photoelectric detectors contain a light source and a light sensor within a sensing chamber. This light source is aimed at an angle away from the sensor, and smoke entering the chamber causes the light to be reflected towards the sensor, causing the alarm to activate [52].

A slowly growing fire that smolders emits more toxic gases and produces larger particles in smoke compared to a flaming fire. This type of fire is commonly associated with burning of household items, for example upholstered furniture that is ignited by a heat source such as a lit cigarette. Conversely, a flaming fire burns faster and hotter and emits smaller particles in smoke. A substantial body of research comparing the performance of different types of smoke detector has reported that upon average, ionization alarms respond fastest in the circumstance of a flaming fire, while photoelectric alarms respond fastest to a smoldering fire (e.g., [20, 24]).

The best type of smoke detector for use in residential settings has emerged as a controversial issue. Public health advocates have argued that photoelectric alarms are superior to ionization alarms for several reasons (e.g., [57]). First, they cite the increased possibility of nuisance alarms that occur with ionization alarms [72], particularly associated with smoke from cooking, leading to decreased functionality because they are more likely to be deliberately disabled by residents. There is certainly evidence in the peer-reviewed literature that ionization alarms are significantly less likely to be functional across time, presumably due to disconnection following repeated nuisance alarms [50]. Second, they also argue that since most residential fires begin as smoldering before transitioning (or not) to flaming, the safest approach is to legislate the use of photoelectric or dual sensor alarms (combination photoelectric/ionization), and have called for a ban on the sale of ionization alarms. There is some evidence that this has occurred in a few regions, for example, a 2007 report for the European Commission on products containing radiation shows that ionization alarms have been prohibited in Switzerland (single, stand-alone units only, with those used as a part of an interconnected system still permitted), Lithuania, and the Netherlands [61]. It is also understood that a small number of states in the USA (Iowa, Massachusetts, and Vermont) may have limited their use by mandating dual sensor alarms (combination photoelectric/ionization). Many other governing bodies have considered this idea, but have not taken it up, primarily because photoelectric and dual sensor alarms are appreciably more expensive than ionization alarms, and it is considered that having an ionization alarm is better than having no alarm at all. Across the world, fire services and fire safety associations widely promote the use of photoelectric or dual sensor alarms as the products of choice for use in residential settings; however, the issue of cost means that ionization alarms remain substantially more prevalent.

Regardless of fire scenario, it is important to note that there is wide variability in the operation of detectors both between and within types, to certain fires. Milarcik et al. [48] statistically compared the performance of different types of residential smoke detection technologies with each other (including ionization, photoelectric, and dual sensor), for differing types of fire (smoldering or flaming) across four published large-scale experimental studies. The findings reported were consistent with the fact that upon average ionization, alarms perform fastest to flaming fires and photoelectric alarms respond fastest to smoldering fires, and when all fires were considered, the dual sensor alarms performed best. However, they also found that overall the difference in response between the technologies was so small as to be statistically equivalent, stating that "…it cannot be determined with confidence which detector technology will alarm first to the next fire" (p. 337). Analysis further showed wide variability between different detectors within each type, regardless of fire scenario. This is compounded by the fact that it is generally unknown which type of fire will next ignite – flaming or smoldering? They concluded that debates about type of detector technology are less instructive and less likely to make a difference to residential fire mortality than efforts to increase the number of detectors present. They argue that increasing the number of detectors in any environment would have the effect of maximizing detection regardless of the circumstances of ignition [48].

Another important factor to be considered is tenability limits. In reference to fire, tenability refers to the ability of an environment to sustain life and is related to things such as heat conditions and toxic gas concentrations. A 2009 study into tenability limits and smoke alarm response reported that flaming fire scenarios produced the most dangerous conditions, with tenability limits exceeded often within just minutes after ignition [47]. Smoldering fires, on the other hand, were found to take much longer to produce untenable conditions, sometimes taking hours to exceed limits. Importantly, it was also reported that alarms of all three types (ionization, photoelectric, and combined) generally provided sufficient time for escape before tenability limits were exceeded for both flaming and smoldering fire scenarios [47]. Although tenability of life is paramount, exposure to smoke poses both acute and chronic threats to health, and therefore, alerting occupants as soon as possible to the presence of fire remains an important consideration beyond survival.

1.3 Standards Governing Smoke Alarms

Standards for smoke alarm signals specify many technical aspects and vary across different countries. Examples in this chapter are provided from the International Standards, the USA, Australia, and the UK only. Additionally, only those in relation to sound pressure level, placement, and signal design (temporal pattern) will be discussed herein. Information about signal pitch is covered in the later section on human response to the smoke alarm, and so, will not be specifically covered in this section.

In relation to sound pressure, although there are subtle variations across nations, the prescribed sound level is commonly not less than 85dBA within a set distance from the sounder (AS 3786 set distance is 3 m; [68]), and no more than 105dBA. The lower threshold is to ensure audibility, and the upper limit is designed to be withstood for short periods without causing hearing damage. This broad rule encapsulates the important notion that an alarm's signal must be loud enough to be heard; however, the same alarm signal may be experienced differently across differing environments. In acknowledgment of this fact, standards usually require that sound pressure be transmitted at a minimum level above the average ambient sound level [e.g., 10dBA above for ISO-8201 [34]; 15dBA above or 5dBA above the maximum sound level having a duration of about 60 seconds for NFPA 72 [51]]. Standards commonly also suggest that the signal should be received at 75dBA at the pillow or bedhead in sleeping areas [9].

Another important specification relates to the placement of alarms. Mandates regarding placement can vary, but the majority of jurisdictions require at least one on each level of a home, with particular emphasis given to placement either within (e.g., USA), or immediately outside the sleeping areas (e.g., UK, Australia). Placement of alarms has a strong influence over the audibility of the alarm signal, as does environmental design. Although the effect is only quite small, a sound will be somewhat amplified in an environment that contains mostly hard surfaces, but somewhat attenuated in an environment in which soft surfaces predominate, such as a bedroom [31]. The same applies to the size of a room, with a sound diminished in a larger space compared to a smaller one [32]. Sound dissipates as it travels, and obviously the further away an operating alarm is from occupants, the less likely it will be heard. Research has shown that the audibility of an alarm signal travelling through walls from a separate room will be substantially decreased regardless of whether the door/s between the alarm and the occupant are closed [32, 43, 49] or open [49]. This attenuation of sound is also affected by the pitch of the alarm signal, with sounds of higher frequency becoming more diminished than those of lower pitch across distances and through barriers [49].

International standards influence some aspects of smoke alarm design and are often drawn upon to inform national standards. For example, International standard 8201 (ISO-8201) titled "Acoustics – Audible and Other Emergency Evacuation Signals" outlines the minimum requirements for aspects relating to the sound emitted by fire alarms and other emergency warning devices that are used across a range of circumstances, including residences and other places where people might be sleeping [34]. It outlines the specifications of the signal that is intended to be used to alert building occupants to the need to immediately evacuate the premises. This standard sets out a repeating three-pulse temporal pattern of 4 seconds duration referred to as the Temporal-Three (T-3). It is comprised of three 0.5 s beeps (on phase), each separated by 0.5 s pause (off phase). Each cluster of three beeps is then separated by a longer 1.5 s pause. The signal should be transmitted at a minimum of 10dBA (decibels; A-weighted sound pressure) above the background noise, and not lower than 65dBA. If it is to be used to awaken sleeping individuals, the minimum sound level is increased to 75dBA at the bedhead, with all doors closed. The standard includes the possibility that a voice alarm can be added with the signal if desired, e.g., Fire! Evacuate! It should be noted that in circumstances where the desired outcome is for occupants to remain in place, then the fire alarm should transmit a distinctly different pattern.

This international standard was designed with the purpose of having a single temporal pattern that would be universally recognizable as signifying the need to evacuate immediately. A standard temporal pattern that is widely recognized by the public is seen as preferable to a voice alarm as it transcends possible misunderstanding that could arise from language barriers. Despite this, historical research has found that signals emitting this temporal pattern are not well-recognized as fire alarm or evacuation signals [27, 56]. Most smoke alarms are now manufactured using the T3 signal, and it is unknown whether recognition has improved in more recent years due to increased familiarity.

2 Human Response to the Smoke Alarm

2.1 Response When People Are Sleeping

Although standards exist to mandate sound pressure and placement of smoke alarms, research examining the best signal to initiate human response was slower to emerge. In fact, early development of smoke alarm technology was focused upon the detection aspects of device design, with little attention paid to signal characteristics beyond the fact that it should be loud enough to be heard [13]. The high frequency beeping noise was used as it was deemed relatively uncommon, and therefore, easy to be distinguished and identified. It was also considered unpleasantly piercing, and therefore, not easy to ignore. From an engineering perspective, it was also cheaper and easier to produce in a small battery-operated device than lower-pitched sounds [9].

By the early 2000s, about 10 years after smoke alarm installation became more widely mandated, accumulated evidence from fire fatality statistics indicated that more residential fire deaths occurred in the presence of an operating smoke alarm than was expected. Examination of these statistics showed that several groups remained at increased risk of death in fire due to individual differences including older (70+) or younger (preschool) age (e.g., [6, 46, 60]), being male, being under the influence of alcohol (e.g., [29, 35, 67, 71]), smoking (e.g., [35, 71]), having a disability (e.g., [1]), and mental health status [70]. The risk becomes compounded when these factors are combined, for example smoking and drinking alcohol (e.g., [5, 54, 70]). A 2015 study comparing outcomes from fatal residential fires to those where all occupants survived further reinforced the importance of human behavior in determining outcomes in residential fire. This study highlighted that taking psychotropic or sedative drugs, living alone, being asleep, and being in the room of fire origin were significant risk factors for death compared to survival [71]. Ahrens [1] also reported that people who died in home fires in the period 2014–2018 where a working smoke alarm was present were more likely to have been in the area of fire origin, have been intimate with ignition, or to have attempted to fight the fire themselves. This highlights the notion that smoke alarms become most important in circumstances when a person would otherwise be unaware that a fire has started, such as while they are sleeping.

It is undeniable that one of the most important risk factors for death in a residential fire is being asleep. The fatality rate in fires is approximately three times greater during the sleeping period than during the waking hours [9]. Recent data from the USA have shown that people who died in home fires where there was no working smoke alarm present were more likely to be asleep than fatalities that occurred in the presence of an operating smoke alarm [1]. Taken together, these facts clearly emphasize the importance of smoke alarms in reducing fire fatalities by alerting sleeping individuals to the possibility of fire.

Factors relating to the environment, the individual, and the alarm signal itself are all important in determining whether a smoke alarm is likely to awaken sleeping individuals. However, as demonstrated above, examination of risk factors for death in fire reveals that individual differences remain an important consideration for smoke alarm design, and different signals have been found to vary in their ability to awaken those most at risk including children, the elderly, people who are hard of hearing, and people impaired by alcohol.

While people sleep their brain remains in an active state, monitoring the external environment for stimuli that may require response [7]. When a signal from the environment is received, it is processed by the brain and examined for significance below the level of conscious awareness. If the signal is processed as lacking in significance, then sleep will be maintained; however, if it is processed as requiring attention, then arousal from sleep will follow. Therefore, it is not simply the loudness of a signal that will predict a response. This is exemplified when we consider that people who live near a railway crossing or airport can very often sleep through the cacophonous sounds that intermittently occur in these environments. The familiarity of the environment renders the sound insignificant.

The significance of a signal can be determined by its novelty, or by learned associations. If an unexpected sound occurs it may signal a situation that needs attention, and wakefulness may follow. Likewise, if a sound is associated with emotional significance such as a person's name, or with a situation signaling danger or provoking action such as the sound of breaking glass, then it is also highly likely that an unimpaired person will awaken very quickly. This is demonstrated by research which showed that people will respond more often to their own name than to a different name in all but the deepest stages of sleep [53]. The importance of learned associations is also highlighted by research demonstrating that people can be motivated or "primed" to respond to specific auditory stimuli while asleep. In 1961 [74], researchers Zung and Wilson conducted a study that attempted to prime participants while awake to respond during sleep to a specific nonthreatening signal (e.g., a doorbell), but not to other similarly benign signals (e.g., a telephone). Their results showed that the response rate to the primed signal increased from 25% to 90% during the deepest stages of sleep.

Along with other work, this has lead psychologists to conclude that the brain appraises the emotional significance of a signal before sleep maintenance or arousal will occur. This has been confirmed by research using brain imaging to show that different areas relating to emotional processing are activated in response to a person's name during sleep, compared to when they are awake [55]. During sleep, emotional stimuli is processed following a different pathway that bypasses the "thinking" part of the brain (cortex) to prompt more immediate arousal, at a lower threshold of sound level, and with a greater chance of causing awakening. The path followed is similar to the one that causes a reflexive fear response when we are awake, and with the same immediacy of readiness to respond. The notion that arousal is affected by signal significance or learned associations can clearly be applied to the design of the smoke alarm signal. It reinforces that the signal should be immediately recognizable and provides support for the use of a standardized signal such as the T-3 pattern when people are asleep, as well as when they are awake.

Given the importance of being asleep as a risk factor for death in fire, research on auditory arousal thresholds (AATs) has been applied to smoke alarm signal design. The term AAT refers to the minimum sound pressure level an auditory signal must reach to be detected by a sleeping individual, causing them to wake. Sleep cycles in stages, moving sequentially from wakefulness through stages 1 to 4, and back again in reverse order before a period of rapid eye movement sleep (REM) is experienced. These cycles recur across the night with about a 90 min periodicity. It can be more difficult or take longer to awaken a person in some stages compared to others. Stages 1, 2, and REM represent lighter sleep, where a person can most easily be roused, and Stages 3 and 4 represent progressively deeper sleep, where a person can be much more difficult to awaken [7]. Most deep sleep occurs in the first third of the night, and after that much more time is spent in lighter sleep stages. As previously explained, standards mandate that a smoke alarm signal should be received at a sound pressure level of at least 75dBA at the pillow, but is this generally loud enough to awaken sleeping individuals? Research using pure sound tones (unrelated to emergency warning signals) has found that the sound pressure necessary to wake one person up may very much vary compared to the next, to the extent that individual differences account for most of the variance in auditory arousal thresholds (AATs; [73]). This study reported that differences in AATs across sleep stages spanning both light (Stages 1, 2, and REM) and heavy sleep (Stages 3 and 4) varied within different adult age groups in the range of 54–82dBA between individuals.

Knowledge from AAT research has been used to inform why sleeping people from the most at-risk groups die despite the presence of a working smoke alarm. Several auditory signals with different spectral complexities have been investigated for their ability to wake people from different vulnerable groups. Spectral complexity refers to the modulation of pitch within a sound, with a pure tone resounding at a single level of pitch, and a square wave resounding across a spectrum of varying pitches. To explain in simple terms, a pure tone might be described as the sound generated when a single key is struck on a piano, whereas a square wave is more closely akin to when a chord combining several notes is played. Other signals including bed and pillow shakers and strobe lights have also been explored. In 2007, Bruck and Ball published a paper summarizing research carried out on the response of sleeping individuals from at-risk groups towards the development of an optimal signal for the smoke alarm. The following section will provide a brief summary of some of the research presented in that paper, adding more contemporary findings where applicable.

As previously highlighted, an important risk factor for death in residential fire is age, with the very young and the very old most vulnerable. It is known that AATs gradually decrease with age across the lifespan, and that it is much harder to rouse a young person from sleep than an older person. Results of a study investigating AATs comparing groups through the childhood years to young adulthood (5–24 years) reported vast differences in average AATs between the youngest group (5–7 years; Mean = 111.6dBA, SD = 12.5dBA) and the oldest group (20–24 years; Mean = 67.8dBA, SD = 21.9dBA). In fact, until early adulthood (20–24 years), the average sound pressure level to provoke a response was considerably above the recommended level of 75dBA to be received at the pillow for a smoke alarm, with the AAT for child groups ranging from 111.6dBA in those aged 5–7 years, to 97dBA for adolescents [22]. These results are in keeping with other sleep studies showing that children experience more deep sleep through the night than adults, and that the deep sleep they experience is qualitatively deeper [2].

When this knowledge is applied to smoke alarm research, studies using different alarm signals have shown fairly consistent results. Early research showed that children aged 6–15 years will not reliably awaken to a high-pitched beeping alarm signal presented at 60dBA [8] or 89dBA [10]. A later study comparing responses of children aged 6–10 years to various alarm signals showed that significantly fewer children responded to the high-pitched (4000 Hz) pure tone alarm compared to a lower-pitched (520 Hz) square wave (modulating 500–2500 Hz) signal. It further showed that voice alarms (including the child's mother's voice using the child's own name, and an actress's voice spoken in urgent tones) were both more successful in terms of the number of children awakened and timeliness of awakenings, compared to the high-pitched alarm signal. However, no advantage was apparent for these two signals when compared to the lower-pitched (520 Hz) signal [15]. These results have been confirmed in recent large-scale studies with children investigating a range of different signals presented at 85dBA at the pillow including maternal voice alarms using the child's name, a female stranger's voice, a male stranger's voice, a hybrid alarm (combining the female stranger's voice and the 520 Hz signal), the lower-pitched 520 Hz square wave, and the conventional high-pitched (approx. 3200 Hz) signal. Regardless of comparative signal, these studies consistently report that the conventional high-pitched alarm performs significantly worse in arousing children from sleep [63–65]. It was further reported that the 520 Hz signal and the female stranger's voice outperformed the signal with the mother's voice using the child's name, confirming the earlier findings of Bruck et al. [15] that personalizing the signal did not improve effectiveness [64].

Although these studies were conducted in the child's own home while they were sleeping in their own beds, all used somewhat contrived methods since sounds were delivered using externally provided audio equipment. Additionally, most delivered sounds using the modified method of limits (i.e., presenting sounds at gradually increasing volumes) in order to determine which signal would prompt awakening at the lowest sound level (i.e., to investigate AATs). A separate project took a novel approach to investigate the response of children to smoke alarms using more naturalistic methods. Bruck and Thomas [14] recruited a community sample of parents of children aged 5–15 years and asked them to set off the home smoke alarm closest to their child's bed, 1–3 h after sleep onset. Home smoke alarms at this time still emitted the high-pitched pure tone (as do alarms in most homes today), and it was reported that 78% of children aged 5–15 years slept through 30 s of alarm presentation (ages 5–10 years 87% slept through, and for 11–15 years 56%).

Age can affect the response to smoke alarms in older adults differently to children. Humans experience less deep sleep as they age, so it seems intuitive that elderly people would have little trouble in responding to a smoke alarm signal. However, as we age, we are also more likely to experience hearing loss, especially regarding sensitivity to higher pitched signals. Cruickshanks et al. [25] studied hearing in the right ear of men aged 48–92 years who were awake and demonstrated that the threshold for being able to detect a tone presented at 3000 Hz was considerably higher than for a 500 Hz tone. From their data, it can be seen that a 3000 Hz signal would need to be presented on average at least 30dBA louder than a 500 Hz signal in order for a 70 year old man from the study cohort to detect it. In 2006 [11], Bruck and Thomas conducted a study investigating the response of sleeping older adults (aged 65–85 years) to different signals including a 3000 Hz high-pitched pure tone T-3, a 520 Hz square wave T-3, a 500 Hz pure tone, and a male voice. Consistent with the findings for children reported earlier, they found that the high-pitched 3000 Hz signal was the least effective of all presented. This signal needed to be transmitted at 20dBA higher volume on average to initiate a response compared to the best signal, which was once again the 520 Hz square wave (T-3). They reported that people aged over 75 were particularly vulnerable to sleeping through the high-pitched alarm, and that the minimum pillow volume of 75dBA was insufficient for this age group if the 3000 Hz signal was used.

Further research investigating the optimal signal to awaken people who are hard of hearing was conducted by Bruck and Thomas [12] for the US Fire Protection Research Foundation. These researchers investigated three auditory signals using the T-3 pattern including a 400 Hz square wave, a 520 Hz square wave, and a 3000 Hz pure tone (high-pitched smoke alarm signal), together with an under mattress bed shaker, a pillow shaker, and strobe lights. They used the modified method of limits (with signals gradually increasing in intensity across time) to determine waking thresholds and found that the 520 Hz square wave was the singular most effective signal, successfully awakening 92% of their hard of hearing participants when presented at 75dBA for 30 s, increasing to 100% when the sound pressure level reached 95dBA. They further reported that 80–83% responded to the bed or pillow shaker (respectively) at the intensity of purchase, and that the bed shaker specifically was significantly less likely to awaken people aged over 60 compared to people from younger age groups. Finally, they reported that strobe lights were not an effective means to awaken participants from any group. They concluded that the best alarm for alerting people who are hard of hearing should likely combine the 520 Hz signal with a vibrating alerting device such as a pillow or bed shaker, based upon the signals they tested.

Finally, the most widely reported risk factor for death in fire is alcohol intoxication. Examination of 17 studies published prior to 2011 showed that where data are collected about blood alcohol concentration (BAC), about half of all fire fatalities tested positive, and about one fifth to one quarter of these were highly intoxicated (defined as BAC .20 mg/dl; [18]). A study comparing demographic, behavioral, and environmental factors for 95 victims of fire from Australian coronial records showed that 58% of fatalities tested positive for alcohol, and 95% of these showed BAC of .10 mg/dl or greater. This study showed that being aged 18–60, the involvement of smoking materials in ignition, having no pre-existing conditions preventing escape, and being male were all significantly associated with fatalities who had consumed alcohol, compared to those who had not [18].

Two studies are known to have used the modified method of limits to examine AATs to different alarm signals when participants were under the influence of alcohol. First, Ball and Bruck [4] reported results of a small pilot study comparing the effectiveness of different auditory signals in awakening self-reported deep sleeping young adults under sober, .05 mg/dl BAC, and .08 mg/dl BAC alcohol conditions. They compared a female voice alarm with the high-pitched 3000 Hz smoke alarm signal, and a 520 HZ square wave T-3 and found that the female voice alarm and the 520 Hz square wave T-3 were significantly more likely to awaken individuals under the influence of both alcohol conditions. Most importantly, analyses also showed that it was significantly more difficult to awaken participants under the influence of alcohol compared to when they were sober, even at the lower level of intoxication [4]. Stochastic modelling using these same data subsequently showed that the probability and estimated waking up threshold for the various alarm signals were different between males and females, with males proving less sensitive (and therefore harder to awaken) than females across all conditions, including under the influence of alcohol [33].

The Ball and Bruck [4] study was a pilot investigation with a small number of participants only; however, their findings lead the US Fire Protection Research Foundation to fund a larger scale project. This larger study compared the response of sleeping young adults (aged 18–26 years) at .05 mg/dl BAC to several different signals, including a 400 Hz square wave, a 520 Hz, a 500 Hz pure tone, a 3100 Hz, a bed shaker, a pillow shaker, and a strobe light, all presented using the T3 pattern [16]. They reported that the 400 Hz and 520 Hz square waves were significantly more effective than the other auditory signals, and woke participants at the AAT of 75dBA or less for 93–100% of participants, respectively. They also reported that bed shakers, pillow shakers, and strobe lights were all found to be ineffective in awakening young people under the influence of alcohol.

In response to the assumption that this is due solely to the pitch of the signal, a study compared signals of different pattern, pitch, and spectral complexity (pure tone vs. square wave). The study tested alarms including beeping signals in the low-to-mid frequency range (400, 520, 800 and 1600 Hz square waves), whooping white noise signals (spanning 400–1600 Hz and 400–800 Hz), and two signals combining square wave (520, 800 and 1200 Hz) and pure tones (400, 800 and 1600 Hz) presented consecutively in order of ascending pitch [17]. All signals were presented using the T-3 pattern to match international standard ISO-8201 [34]. Results showed that the lower-pitched 400 and 520 Hz square wave signals produced significantly lower AATs compared to the other signals. The researchers concurred with previous work to conclude that the 520 Hz square wave signal would be their recommended sound for the smoke alarm signal [17].

Across all studies reported here comparing the effectiveness of different signals in awakening people who are most at risk of death in fire, a remarkably consistent finding is that the 520 HZ square wave T-3 has been found to be the most successful. However, it is important to note that unimpaired adults generally respond very well, regardless of signal. Although statistical differences are found between AATs for different alarm sounds, for unimpaired adults these differences are in the magnitude of 1–2 s [66] and are so small as to be unlikely to alter outcomes in the case of a home fire. However, as has been demonstrated, the same cannot be said for vulnerable groups. When considering this body of work, it is important to note that these studies necessarily contained an element of priming, in that participants were usually aware that the intention of the study was to wake them up with a signal after sleep onset. Nonetheless, there was also an attempt to preserve ecological validity by carrying out the procedures in a person's own home while they were sleeping in their own bed. Furthermore, the priming effect was equal for all signals. A pleasing result from the extensive body of work presented within this chapter is that local standards in several countries now mandate a 520 Hz signal for new smoke alarms (e.g., Australia) or for all smoke alarms to be used in areas where people are sleeping (e.g., USA). This progress acknowledges the elevated risk for death in fire that is associated with a raft of individual human characteristics and behaviors.

2.2 Response When People Are Awake

Despite the historic intention of smoke alarms in residential homes to wake people up during fire emergency, they were originally used in large and public buildings to alert people to the presence of fire when they are generally awake, but possibly unaware. Beyond the design and technical features of smoke alarms, *people* play an integral role in their effectiveness as a fire safety measure. Hence, it is pertinent to consider how people might respond to a smoke alarm signal they become aware of. Ideally, when an alarm signal sounds, awake people should respond immediately by ceasing all prior activity and moving quickly to the closest building exit for evacuation, unless directed otherwise. Despite general knowledge of this protocol, it is remarkably common for people to not respond in this way, but rather to continue with their prior activities, delaying evacuation and decreasing the time available for safe retreat [44]. As a result, pre-emergency activity has become a point of interest for human behavior in fire research and has provided some surprising results. For example, information from 375 evacuees of a 32-story high-rise office building fire in the US revealed that 65% of people either continued with their prefire activity and/or waited for clear instructions for action before responding to the alarm

[40] - But why is it that people do not respond to smoke alarms as intended? A number of underlying psychosocial factors can explain this lack of response to emergency signals, including the smoke alarm.

First, a necessary precursor for action is attention. If a person does not pay conscious attention to sensory information (i.e., smoke alarm signal), then that information is unable to be cognitively processed any further, and therefore is unable to be acted upon [21]. Attention directed towards prior activities can hinder the recognition of, and response to, smoke alarms. When a person is immersed in an activity at the time a smoke alarm sounds, even when that activity seems unimportant (e.g., watching TV, working on a computer, playing video games), they may fail to pay attention to the auditory sensory cue and continue with their activity as normal. In a similar way to someone who may be asleep, this unintentional ignorance is the result of attentional bias towards the prior activity impeding the taking in of new, unrelated (fire cue) information [38].

However, even when people are aware of and pay attention to a smoke alarm signal, this does not guarantee action. Even when smoke alarms are noticed, the absence of other obvious cues may make the signal ambiguous, and people may continue with their preexisting activity until a cue that is more explicit and/or intense is perceived [45]. The frequency, intensity, consistency, and credibility of cues all inform a person's perception of fire threat [26, 41]. The credibility of smoke alarms can be compromised by previous exposure to false alarms as people draw on their past experiences to inform decision-making in new situations [38]. Hence, a history of previous false alarms can result in a biased and incorrect interpretation of real alarms [37]. The way a person perceives the nature and intensity of a smoke alarm and their analysis of their own personal risk will influence their subsequent action or inaction [23]. More specifically, a person who interprets a significant fire threat (e.g., fire in close proximity) is likely to respond more readily than a person who perceives the risk to be low (e.g., fire on another floor of a building) ([41, 62]). A study by Gerges et al. [28] found that 74% of people reported they would ignore a fire alarm completely, yet "getting the kids and leaving" and "leaving immediately" were the top two ranked actions reported if visual fire cues were observed (i.e., flames and smoke).

In addition to drawing on our past experiences for information to guide our behavior in a similar situation, people also seek information from their social context. Irrespective of individual personality differences, our behavior in social settings is largely determined by a set of social scripts, known as schemas, which we develop over the course of our lives. These scripts help us to function effectively in social settings because they provide us with a set of norms, or rules of how to behave and predictions of what to expect from other people. These schemas provide us with knowledge regarding protocols for expected behavior in familiar situations (e.g., cooking dinner at home, ordering a coffee at the café, or attending a football match). Even in unexpected emergency events people adhere to social expectations relevant to the (non-emergency) context they are in [39]. For example, people eating dinner in a restaurant may be reluctant to evacuate immediately because social rules require them to pay for their meal before leaving. Likewise, people living in an apartment complex may not consider fire safety as their responsibility unless they are designated a role, e.g., as a fire warden. In addition, when faced with a somewhat ambiguous or novel situation where our schemas are not particularly strong, people may seek guidance by observing the behavior of others.

The presence and behavior of other people in social situations influences our own behavior significantly. In fire emergencies, people can be leaders or followers, but most commonly take on the follower role when others are present. This means they may not immediately respond, but will wait to be guided by the actions of others [39]. Over 50 years ago, Latane and Darley [42] conducted a pivotal study on social influence, or the 'Bystander Effect' in fire emergencies. Participants were seated in a waiting room that subsequently began to fill with smoke and were exposed to one of three conditions including alone, accompanied by other naïve people, or accompanied by deliberately passive study confederates. Findings revealed that participants were most likely to report the smoke when alone (75%), and to do so more swiftly. Alarmingly, when people were with others, only 10% of those seated with the passive confederates and 38% of those with naïve people reported the smoke. Three underlying psychological mechanisms are proposed to mediate the influence of passive bystanders. These include diffusion of responsibility (i.e., the belief that someone else will speak up/act when in the presence of others); evaluation apprehension (i.e., the fear of making an inaccurate interpretation of a situation and taking subsequent socially incorrect actions that will be observed by other people); and pluralistic ignorance (i.e., the assumption that others "know better" when the situation is ambiguous; [42]). Evidence from a recent replication study supports the negative influence of passive occupants on the inaction of others [36]. However, this study also found a positive influence of proactive bystanders, whose evacuation behavior was followed. It appears that when a fire cue is ambiguous, people seek guidance about behavior by observing others. If other people remain passive, this leads to a reduction in threat perception.

Presumably, fire drills will alter human behavior by reinforcing a schema of the best way to respond. However, research on egress has focused very much on collecting data to be input into evacuation models used by fire engineers, and much less focus has been on how people actually perform in a real fire emergency as a result of taking part in fire drills. Furthermore, exposure to repeated fire drills can have the reverse of the desired effect by creating a contempt of false alarms [30]. This does not mean that fire drills are not important, or that they do not change human behavior, but rather that more work needs to be done to investigate their real-world impact.

3 Conclusion

The body of research on human response to smoke alarms has provided important information that has been used to improve their effectiveness in the decades since their first inception. However, this research also shows that their effectiveness should not be naively considered as a safety guarantee. As described above, there are many factors involved in the smoke alarm-human response interaction. The reality is there are times when people will not respond to fire alarms – regardless of whether they are awake or asleep. The research presented in this chapter clearly demonstrates that smoke alarms save lives in residential settings. It has also clearly shown that different types of smoke detector are best suited to sensing different types of fire. There are segments of the community that strongly advocate for the use of the more costly photoelectric smoke alarms over the less expensive ionization units, but the research clearly supports that it is better to have any type of smoke alarm, than to have none at all.

There is also a substantial body of research that has investigated the optimal pitch for the smoke alarm signal when it is to be used to awaken people who are sleeping. This research has overwhelmingly supported the use of a 520 Hz square wave signal as superior in waking vulnerable groups compared to other signals tested. This includes the much used high-pitched alarm that until recently was universally used in commercially available smoke alarms. Pleasingly, engineering standards in many jurisdictions now specify the use of the 520 Hz signal, especially when the alarm is to be used to alert sleeping individuals.

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