Reducing Fire Deaths in Older Adults: Optimizing the Smoke Alarm Signal

Research Project

Investigation of Auditory Arousal with Different Alarm Signals in Sleeping Older Adults

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FOREWORD

Smoke alarm and signaling systems are a proven strategy for reduction of fire fatalities in the general population. However, studies have shown that the elderly do not fully benefit from conventional smoke alarm systems, particularly during the sleeping hours. In April of 2005, the Fire Protection Research Foundation was awarded a Fire Prevention and Safety Grant by the US Fire Administration for a new project to study this topic.

A portion of the study involved the conduct of human behavior studies to investigate the arousal thresholds from sleep in older adults to the current US smoke alarm and compare these thresholds to several alternative signals, and to investigate the performance abilities of older adults when awoken suddenly by an alarm. This report presents the results of this portion of the study.

The overall goal of the project is to optimize the performance requirements for alarm and signaling systems to meet the needs of an aging population. The balance of the study is presented in a companion report also published by the Foundation entitled "Reducing Fire Deaths in Older Adults: Optimizing the Fire Alarm Signal".

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The content, opinions and conclusions contained in this report are solely those of the authors.

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Investigation of auditory arousal with different alarm signals in sleeping older adults

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Report for the Fire Protection Research Foundation
for the 2005-2006 US Fire Administration Grant
"Reducing fire deaths in older adults: optimising the smoke alarm signal."

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Executive Summary

Over the last decade research on which emergency signal will best awaken sleeping individuals has led to a recognition that more work is needed on the audibility of existing smoke alarms and the comparative waking effectiveness of alternative signals. This research focuses on these issues in a population known to have an elevated risk of dying in a fire, adults aged over 65 years. It investigates responsiveness to different signals in sleeping older adults as well as measuring performance upon awakening (sleep inertia). This comparison of arousal thresholds required a tightly controlled experimental design, with selection criteria and methodological requirements that increase the validity of such comparisons using a manageable sample size, but do not allow direct extrapolations to the field in terms of expected arousal thresholds in a real emergency or percentages of the population that may awaken to certain signals. These population and methodological factors probably result in the research to date *underestimating* the proportion of people who will not wake up to an alarm.

Aims and the relevant findings are set out below, followed by a discussion of the key conclusions and recommendations.

Responsiveness to signals:

Arousal thresholds to different sounds were determined by playing auditory signals to the participants (aged 65-85 years, n=42) when they were in deep sleep (slow wave sleep). Each signal was presented with a stepped increase in volume from 35 dBA to 95 dBA and a bedside button was pressed by the participant to indicate awakening. The same participants received all four signals over two nights.

Aim 1: To investigate the arousal thresholds from sleep in older adults (aged 65- 85 years) to the current US smoke alarm (a high frequency T-3) and compare these thresholds to several alternative signals. The three alternative signals were a mixed frequency T-3 signal, a male voice (saying Danger, Fire, Wake up) and a 500 Hz pure tone in a T-3 pattern.

The first hypothesis was that the older adult sample would have significantly higher auditory arousal thresholds to the high pitched T-3 signal than to the two signals of mixed frequency (the mixed T-3 and the male voice). This hypothesis was only partially supported, with the results showing that the volume needed to wake up to the high T-3 was significantly higher than that needed with the mixed T-3. The most important findings were that,

(a) the **older adults needed a lower volume to wake to the mixed frequency T-3 signal** (median = 45 dBA) than to the other three signals tested (male voice, 500 Hz T-3 and high T-3), and

(b) the **current high frequency T-3 needed the highest volume** (median= 65 dBA) to produce awakenings compared to the other signals.

The second hypothesis was that the older adult sample would have significantly lower arousal thresholds to all signals than a young adult sample tested under similar conditions. Mean values showed differences in the predicted direction for both the mixed and high T-3 signals but only for the mixed T-3 was the difference across age groups significant. Surprisingly, for the male voice signal the young and older adults woke to similar volumes. Individual responses from three participants of non-English speaking background (NESB) suggested that a voice alarm with English text would not be suitable for them, although the inclusion of such NESB people did not cause the overall poor performance of the voice alarm with the older adults. Overall, these results indicate that **for older adults a male voice alarm would not be a suitable alternative**.

Sleep Inertia: This study was the first to assess older adults on several cognitive and physical tasks after awakening, and compare such performance to pre–sleep (baseline) levels.

Aim 2: To investigate the performance abilities of older adults when awoken suddenly by an alarm. This sleep inertia was assessed in terms of their simple and complex cognitive functioning and physical performance (with the latter involving a psychomotor task plus getting out of bed and walking 15 metres).

The results suggest that a **decrement in physical functioning of around 10-17%** may be expected across the first five minutes after awakening. **No important effects on simple or complex cognitive functioning were evident**. There was a wide variation in performance across individuals, with perfomance under baseline conditions strongly predicting performance under sleep inertia conditions.

Conclusions and Recommendations:

The present study, using a rigorous design and sufficient sample size of sleeping adults aged over 65 years, has found a substantial difference in the median auditory arousal threshold of 20 dBA between the current high frequency T-3 and the best performing alternative signal tested. Thus all the available data testing the waking performance of smoke alarm signals shows that a high frequency alarm signal[1] performs the *most poorly* of the alternatives tested for waking all the different population groups tested so far (i.e. children, sober and alcohol intoxicated young adults, older adults aged over 65 years). The evidence is sufficient to lead to the following recommendation:

Key Recommendation: The high frequency alarm signal currently found in smoke alarms should be replaced by an alternative signal that performs significantly better in awakening most of the adult population, once the nature of the best signal has been determined.

The findings of the current study, together with previous literature, indicate that a mixed frequency T-3 signal has *performed significantly better* than a high frequency signal in its ability to awaken sleepers in every sample group tested so far. This includes children, young adults (sober and alcohol intoxicated) and older adults. Voice signals appear to be as effective as the mixed T-3 in the children and young adult groups, but are less effective than the mixed T-3 in the older adults.

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[1] A high frequency signal is typically used in all smoke alarms, the literature reported here has variously tested both a high frequency T-3 signal or continuous pulsing high pitched beeps.

The implications of introducing a signal frequency recommendation into the standards for smoke alarm notifications are considerable, involving a retooling of the entire industry. In view of this, any signal change that is mandated must be done on the basis of rigorous evidence that the best signal has in fact been found. The research is not yet at this point. A brief outline of suggestions for future research is set out below. These may take two to three years to complete.

In the meantime there are some recommendations that can increase the chance of sleeping individuals waking to a fire.

(a) Encourage interconnected alarms. Interconnected alarms that include an alarm in each bedroom will mean that the volume at the pillow is likely to be above 85 dBA.

(b) Consider the special emergency awakening needs of "normal hearing" older adults. Given the hearing thresholds for high frequencies of older adults it is inadequate to require their current high frequency smoke alarm to be a minimum level of 75 dBA at the pillow. The current study shows that those aged over 75 were particularly poor at waking to the current high T-3 (median of 70 dBA for high T-3 compared with 40 dBA for the mixed T-3). One possibility would be to recommend that older adults should have interconnected alarms, or at the very least stand alone alarms (with the current signal) in their bedroom. An additional, more satisfactory, possibility is for smoke alarm manufacturers to market special alarms for this age group that emit a mixed T-3 signal and suggest placement, as a minimum, in the bedroom.[2]

The *future research* that should be completed prior to the mandating of a specific signal encompasses a variety of issues.

(a) Research is needed to determine the optimal pitch and pattern of an alternative signal to wake people up, using a single convenient population, such as young

[2] Such a mixed frequency alarm would also be beneficial for individuals of any age who know they have high frequency hearing loss.

adults. The option of a voice alarm should no longer be considered for adult populations. Alternative pitches and pitch patterns should be investigated within the T-3 temporal pattern, at least in the first instance.

(b) Once several signals have been shown to have the lowest auditory arousal thresholds in the one population tested, they need to be tested in other sleeping populations, especially those most at risk of dying in a fire or of sleeping through an alarm signal. The signals should also be tested for salience and/or urgency as an emergency notification signal requiring action in awake individuals.

(c) Because of the inability to generalise data from the current study to field estimates, further research is needed using large numbers of non-primed, unselected groups to yield population based estimates of waking effectiveness. It seems most likely that the research to date may be significantly *underestimating* the proportion of people who will not wake up to an alarm. This arises from a range of factors, including the important fact that almost all of the participants in the relevant empirical studies on alarms and sleep have been primed to expect that a signal will go off on one of several nights.

(d) A study characterising the spectral characteristics of the background noises in a range of "typical" bedrooms would be informative and relevant. The extent of possible masking can be determined by combining this information with the acoustical characteristics of the signal that is most likely to awaken sleepers.

1 Introduction

Around the Western world the number one priority for residential fire safety has been promotion of the installation of smoke alarms. However, when residential smoke alarms were first developed and widely distributed in the 1970s the focus was on the technology to detect heat and/or smoke and little attention was paid to the nature of the audible signal. A high frequency signal was easily generated by a small piezo device and this was included as the standard alarm signal. As noted by Berry (1978), the issue of the audibility of fire warning equipment was relegated to an Appendix of the NFPA (74-1975) and the assurances about the ability of the signal to awaken people that were provided in the Appendix were at variance with the published auditory threshold data available at the time. Fire code standards include specifications of the volume that the alarm must emit, typically as a range of volumes which are above the ambient sound pressure level (e.g. 10 dBA above ambient, and within the range of 65-105 dBA, AS1670.1-2004). Recommendations about the volume that the alarm must be received inside a bedroom were added and these are generally 75 dBA (e.g. USA, Canada and Australia) at the pillow. A caution that this level may not be adequate to awaken all sleepers is often included (e.g. AS1670.1-2004). ISO 8201 "Acoustics- Audible Emergency Signal" defined a temporal three pattern (T-3) in 1987 and this was adopted by the NFPA in July 1996 (and later by many other countries) as the required fire notification signal, including in smoke alarms. No recommendation as to a frequency level of the sound is included.

The U.S. Consumer Product Safety Commission initiated a project in 2003 (Lee, Midgett, & White, 2004) to review the sound effectiveness of residential smoke alarms, with a focus on children (who had been shown to not reliably awaken to a smoke alarm) and older adults (who have death rates in residential fires of more than twice the national average). Among the recommendations was the need for further research examining what deficiencies exist regarding the **audibility of current smoke alarms**. Furthermore, previous research has raised the possibility that an alarm of a **different frequency and/or different sound** may be more effective for waking sleeping individuals.

This project empirically investigates both issues with regard to sleeping individuals aged 65 to 85 years. The results may have implications for the development of a more effective alarm signal for smoke alarms. The study also examines increased cognitive confusion and performance impairment (sleep inertia) that may influence effective and timely evacuation behaviour upon awakening in an older adult population.

2 Review of Literature

2.1 Signal significance and characteristics

Contrary to popular belief the brain does not "shut down" during sleep. During sleep we continue to monitor the environment and selectively respond. Discrimination between different signals clearly occurs during sleep, showing that the arousability of an auditory signal is not simply a function of how loud it is. Because cortical analysis of the meaningfulness of a signal precedes arousal, people respond selectively to signals, depending on the level of significance to them. An early study found that sleeping participants responded more often to their own name than to other names (Oswald, Taylor & Treisman, 1960). Significance can be added to a signal by "priming" the person to respond to some signals (e.g., a doorbell), but not to others (e.g., a telephone). When participants were primed to respond to a certain signal presented during the deepest stage of sleep, awakenings increased from 25% to 90% (Wilson & Zung, 1966). Clearly, signal significance and interpretation will affect arousal likelihood and thus it is important that any emergency signal has a unique sound quality that allows it to be readily identified and easily discriminated from other electronic beeping sounds in our environment (car alarms, mobile phones, microwave ovens, etc.).

It has been found, using functional MRI technology (Portas, Krakow, Allen, Josephs, Armony & Frith, 2000), that sounds that have an emotional significance have lower arousal thresholds and an increased probability of waking up a person. The involvement of a central nervous system "pathway of learned fear" has been suggested, with a key implication being that during sleep the emotional content of a signal may be processed independently of cortical input about the meaning of the signal. Thus the use of sounds which arouse our emotions, such as a voice conveying an urgent message, may be an important consideration in emergency signals.

There is now an important body of literature about auditory alarms signals and their interpretation by individuals when awake (Edworthy, Loxley & Dennis, 1991; Edworthy and Stanton, 1995) and this has lead to design criteria suggestions to improve the effectiveness of emergency notifications in awake populations. It has been reported that signals that produce the highest ratings of perceived urgency were those with a higher frequency, a fast speed (tested across 0-500 msec), and a high level of loudness (Haas and Edworthy, 1996). The frequencies tested were across the range of fundamental frequencies from 200 Hz to 800 Hz, where each had higher component frequencies. The one that was perceived as most urgent had a fundamental frequency of 800 Hz with components of 800, 1600, 2400, 3200 and 4000 Hz .

A few studies have evaluated the alerting capabilities of alarms that are not auditory, specifically strobe lights and vibrating tactile devices located on the bed (Bowman, Jamieson & Ogilvie, 1995; Ashley, Du Bois, Klassen & Roby, 2005) especially in the context of emergency arousal for the hearing impaired. These devices are beyond the scope of the current literature review and research, which will focus exclusively on different auditory emergency devices. One reason for this selectivity is that auditory alarm devices are likely to be much lower in cost. Four types of alarm signals will be considered in this review; the high frequency beeping alarm, the Temporal 3 pattern, voice alarms and naturalistic sounds. Note that the literature evaluating their differential waking capabilities will be reviewed in Section 2.3.

A **high frequency beeping noise** is the most widely available smoke alarm signal and was most likely chosen for residential smoke alarms as high frequencies are rare in the normal environment, so they are likely to be more easily differentiated from other sounds. In addition they are subjectively piercing, not easily ignored and small battery operated devices can easily generate such sounds. Most residential smoke alarms emit beeps of a single high frequency which may be between 3000 Hz and 5000 Hz (Nober, Peirce & Well, 1981a; Ball and Bruck, 2004a; Ashley, Dubois, Klassen and Roby, 2005) with a sound intensity in the vicinity of 85 dBA at 10 feet (the latter is a requirement in the US per UL217). Earlier smoke alarms sometimes combined two modulating signals peaking at 2000 Hz and 4000 Hz (Kahn, 1984).

A high frequency signal, however, appears to have several drawbacks. The most obvious disadvantage is that those with high frequency hearing loss (a part of normal aging) will have more trouble hearing the signal (see Section 2.3.3). A further disadvantage of a high frequency signal is that high frequencies are more easily reduced by doors and walls than frequencies below 500 Hz. This reduction occurs because walls reflect the energy from high frequencies rather than transmit it. For low frequencies more energy is transferred through the wall rather than being reflected. Thus, sound reduction is lower at low frequencies and higher at high frequencies (e.g. above 2000 Hz). Figure 2.1 shows transmission losses in dB as a function of the frequency of the sound and the surface mass of the material (e.g. a wall). It can be seen that transmission losses vary by about 20 dB for material of the same surface mass, depending on whether the frequency of the sound is low or high.

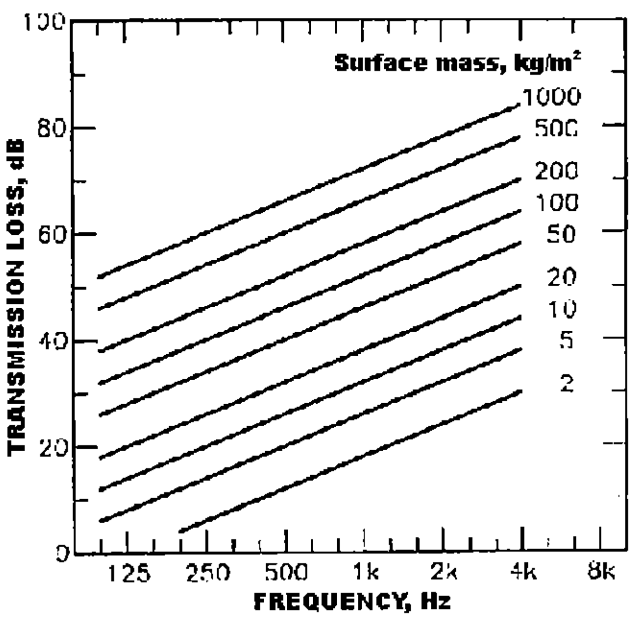

Figure 2.1: Sound transmission losses as a function of frequency of the sound and surface mass of the material through which the sound is being transmitted (from Quirt, 1985).

Robinson (1986) reported that the sound loss from the corridor to the room with the door open was about 12 dB for all frequencies above 500 Hz, with the closure of a door typically contributing another 15 dB, increasing to 20 dB if the door was edge sealed. This data suggests it would be impossible for a 90 dB smoke alarm located in the hallway to reach the pillow at 75 dB if the door was closed. Similarly, others have reported that a hallway smoke alarm will penetrate a closed bedroom door with a resulting bedside volume of between 51 and 68 dBA, depending on the room configuration and materials (Nober, Peirce & Well, 1981b). More recently, Lee (2005) completed a study on the audibility of smoke alarms and noted that bedroom doors attenuate a smoke alarm signal by about 10 dBA, while each home level attenuates the signal by about 20 dBA.

Clearly an alarm signal needs to be louder to awaken a sleeper if significant background noises, such as air conditioners exist (see Section 2.3.1). Masking occurs when the presence of one sound inhibits the perception of another. The greatest masking occurs when two sounds are similar in frequency. Importantly, a signal with multiple frequency components is less likely to be masked than one with fewer frequency components (Lawrence, 1970).

The unimpaired human ear is not equally sensitive to sounds at all frequencies and it is especially sensitive to frequencies between 1000 Hz and 3000 Hz when awake. However, as the change in sensitivity with frequency is most notable at reduced sound intensities, especially below 55 dBA (Lawrence, 1970), this may not be a major issue in determining the optimal frequency for an alarm signal. (Where industry recommendations and standards are for a minimum alarm sound intensity of 75 dBA at the pillow.)

In various Western countries (including the US and Australia, but not Canada) smoke alarms are now being sold which emit the **Temporal- Three (T-3)** pattern. The International Standard ISO 8201 -1987 (Acoustics – Audible Emergency Evacuation Signal) defines the T-3 signal and the specific temporal pattern of the T-3 is as shown in Table 2.1. The International Standard does not limit the smoke alarm signal to any one sound, so signals of different frequencies and acoustic characteristics can be used within the T-3 pattern. The aim is that people will recognise the specific timing pattern as the signal to evacuate immediately.

Table 2.1: One cycle of the temporal pattern of the T-3 evacuation signal.

SIGNAL ON	0.5 sec
SIGNAL OFF	0.5 sec
SIGNAL ON	0.5 sec
SIGNAL OFF	0.5 sec
SIGNAL ON	0.5 sec
SIGNAL OFF	1.5 sec

One study (Proulx & Laroche, 2003) set out to assess people's recollection and identification of the T-3, as well as how urgent the signal was perceived to be. Results showed the T-3 was rarely identified as a smoke alarm or evacuation signal and was not judged as conveying urgency. The T-3 was usually judged to be a domestic signal, such as a busy phone tone.

There is a considerable body of literature about the possible use of the **human voice** in alarm signals. The appeal lies in the fact that a voice message can directly convey both meaning and emotional significance. Individuals hearing voice messages can successfully identify the emotions intended (Banse & Scherer, 1996). Moreover, the words used and the manner in which the words are spoken can influence their believability, appropriateness and sense of urgency (Edworthy, Clift-Matthews, & Crowther, 1998; Hellier, Edworthy, Weedon, Walters & Adams, 2002). It has been argued that humans have a particular cognitive specialisation for speech perception (Liberman & Mattingly, 1989). Phonetic perception may be immediate, with no translation of patterns of pitch, loudness and timbre being necessary. Language, unlike other forms of communication, may operate at a level that is precognitive. If this is the case when awake, then humans may also be particularly tuned to speech sounds during sleep.

A higher pitch is associated with a more intense emotion (Bachorowski & Owren, 1995), and the female voice is correspondingly assessed as more urgent than a male voice (Hellier *et al.*, 2002). Infants have been found to be selectively more responsive to tones at lower frequencies (Weir, 1976), perhaps because these are associated with human speech. The parameters of pitch of human speech show it to be a complex sound, generally below 2500 Hz . While prerecorded voice messages have been found to be helpful in encouraging people to evacuate, studies of warnings in large public spaces such as train stations (Proulx & Sime, 1991) show that a live directive voice announcement is highly effective. Clearly, such an announcement overcomes people's concern that it might be a false alarm. The key disadvantage of a voice alarm is that the signal must be designed to meet standards for both audibility and intelligibility (Grace, Woodger & Olsson, 2001). In addition, the speakers required to produce a quality, loud voice may not be able to be housed in the current small smoke alarm units.

Innovative research has used Gibson's theory of perception (Gibson, 1979) and information processing to test whether alarms that closely match their **naturalistic** intention or meaning are more effective than the more usual beeping signals. In an intensive care ward within a hospital, alarm signals were developed that closely matched the emergency situation they were aiming to alert staff about (Stanton & Edworthy, 1998). It was found that the naturalistic alarm signals were more effective than the standard signals in alerting novice medical staff who had little or no training of the standard signals. Building on this research, Ball and Bruck (2004b) set out to design a more meaningful, perhaps also emotional, signal. The first stage of this was to ask people which sounds would (i) make them feel a negative emotion, (ii) draw their attention when sleeping, and (iii) make them feel the need to investigate upon awakening. Collating 1447 responses showed that for all three questions people overwhelmingly nominated sounds within three categories; expressions of *human emotion* such as a baby crying or a person screaming, *manufactured alerting sounds* such as a smoke alarm, and other sounds that may *naturalistically* alert them to the possibility of danger, such as the sound of footsteps. Two new sounds (conveying either emotional and naturalistic signals) were developed with the aim of testing their ability to awaken sleeping people in a fire emergency. As the *naturalistic* sound needed to be situationally congruent and indicate a fire, a signal consisting of house fire sounds (fire crackling, roaring and popping, together with glass breaking) was developed. For a signal conveying human *emotion*, ethical considerations ruled out using genuine sounds of human distress. The second signal developed was a female actor's voice conveying human emotion through an urgent voice tone and choice of words (danger, fire etc). The testing of these signals is described in Section 2.3.1 below.

Naturalistic fire cues were also used in a study (Bruck & Brennan, 2001) with the aim of determining whether adults would awaken to low level fire cues, including two auditory cues. Both the crackling sound of a fire and a "shuffling" sound (as reported by fire survivors) were presented to sleeping individuals at very low levels (received at 38 to 48 dBA) and a relatively high rate of arousal was found (91% to crackling and 83% to shuffling).

It is not unusual for smoke alarms in buildings to move through a **signal shift**, or a series of different signals, such as beeping tones with different temporal and frequency patterns and whooping tones. Although it has not previously been investigated, anecdotally such shifting makes sense, as a signal that is constantly changing is likely to attract attention (when awake or asleep). We know that sometimes people can sleep while a TV is on, only to wake up when it is turned off. The change in auditory signal, even to silence, may induce arousal. Moreover, studies of auditory arousal thresholds (see below) consistently note major individual differences in thresholds and it is possible (but not established) that different people may respond better to different signals and shifting signals increase the chance that one of the signals will be perceived more easily by some people and acted upon. To date only one study (Ball & Bruck, 2004b) has tested the efficacy of a signal shift pattern in sleeping individuals and this will be discussed below in Section 2.3.1

2.2 Human characteristics

There are a wide range of factors that affect the auditory threshold of a person while asleep. These have been discussed in some detail in two earlier review papers (Bonnet, 1982; Bruck, 2001) and only the most relevant and important points will be summarised here. In this section discussion will focus on research using signals that are not emergency alarms, such as pure tones. Alarm research and sleep will be reviewed in Section 2.3 below. The literature shows that the issue of what will wake different people under different circumstances is complex.

Of all the possible variables it seems that **individual differences** account for the most variability in auditory threshold. One study examined responsiveness to a 5 second 800 Hz tone during sleep (Zepelin , McDonald & Zammit, 1984) in people in various adult age categories, across three different stages of sleep (REM, stage 2 and stage 4). It was found that the thresholds varied for each age and sleep stage data point by at least 54 dBA with the largest range being 82 dBA (i.e., range from 39 dBA to 121 dBA for people in their 40's being awoken from stage 2, see Table 2.2). It is known that people's individual susceptibility to being awoken is quite consistent from night to night and within a night and that those who tend to sleep more deeply will do so in every stage of sleep, relative to those who sleep more lightly in all stages of sleep (Bonnet, Johnson & Webb, 1978). Moreover, once an individual is asleep, the issues of whether they are a good or poor sleeper (i.e., awaken frequently) do not appear to be an important variable (Johnson, Church, Seales & Rossiter, 1979).

Age is likely to be the next most critical variable, with major differences between the arousal thresholds of children, middle-aged adults and elderly individuals. Older people are likely to awaken more easily than younger people and children are generally the hardest to arouse (Busby, Mercier, & Pivik, 1994; Zepelin *et al.,* 1984). Table 2.2 shows the gradual reduction in arousal thresholds across three different adult age groups, in both stage 4 and stage 2. Zepelin *et al.* (1984) found that the decline was sharpest in stage 4 sleep, but occurred in stage 2 and REM as well. The authors concluded that age was not as influential as individual differences in accounting for the auditory arousal threshold levels, but age differences were nevertheless substantial, with the decline becoming evident by the 40s.

Table 2.2: Auditory awakening thresholds (dB) to a 5 second 800 Hz tone at three different age levels by stage of sleep (n=52). Data from Zepelin *et al.* (1984).

		Stage 4	Stage 2
18-25 yrs	mean	101	82
	standard deviation	17	22
	range	49-116	45-121
40-48 yrs	mean	87	71
	standard deviation	20	22
	range	59-116	39-121
52-71 yrs	mean	71	61
	standard deviation	20	13
	range	39-116	44-98

There may be several factors operating that mean arousal thresholds decline with advancing age. Perhaps the most important is the age related change in electroencephalogram (EEG) energy levels (based on power spectrum density) within sleep. Adult EEG energy levels (documented across ages 18 to 43 years) show a decline with increasing age (Astrom & Trjaborg, 1992). Secondly, the duration of the deeper parts of sleep (slow wave sleep, SWS, consisting of both stage 3 and 4 sleep) reduces with age so that younger adults spend more time in SWS than older adults. The decrease is especially evident in the amount of stage 4 sleep in the older individuals and more so in men than women. In some cases stage 4 may disappear in people over the age of 60 (Carskadon and Dement 2000). A recent meta-analysis concluded that the minutes of SWS decline with age such that at age 65, 75 and 85 we could expect 67 min, 50 min and 25 min respectively of SWS (Ohayon, Carskadon, Guilleminault, Vitiello, 2004).

The ability to be awoken in different **sleep stages** varies. Stages 3 and 4 are subjectively the deepest part of sleep and predominate in the first third of a night of sleep. Most studies show (see Bonnett, 1982 and Section 2.3 below) that it is harder to arouse a person from stage 4 compared to all other sleep stages and that arousal thresholds are approximately equal in stage 2 and REM. However, the average difference in decibel level needed to awaken an adult in different stages may not be substantial. For example, Table 2.2 shows that Zepelin *et al.* (1984) found mean differences across nine 52-71 year olds of only 10 dB between stage 2 and stage 4 sleep, while individual differences, as shown by the range values, are much greater (50-80 dB). Time of night differences, independent of sleep stage, do not appear to be robust (Bonnett, 1982).

Several studies have considered how **sleep deprivation** affects people's ability to respond to auditory signals when asleep. In some cases the experimental design relies on successful tone discrimination, or reaction time, rather than considering thresholds specifically. Performance is consistently reduced by sleep deprivation across a range of studies (Williams, Hammack, Daly, Dement & Lubin, 1964), even after just one night of partial sleep restriction to four hours (Synder & Scott, 1972). An early study (Lindsley, 1957) found that after 38 hours of sleep deprivation sleeping participants reacted to a tone less frequently than on control nights (only 600 times compared to 1500 times), suggesting increased thresholds. It is well known that sleep deprivation changes the architecture of sleep on the recovery nights, with considerably more stage 4 sleep in the first third of the night. It also seems likely that EEG energy levels increase across all sleep stages in recovery sleep, presumably making it harder to arouse the sleeper.

Most early studies found no significant **sex differences** in arousal thresholds. However, there were some exceptions. Wilson & Zung (1966) found more responsiveness among sleeping women than men to sounds they were motivated (by a reward) to respond to, while Zepelin *et al.* (1984) found a trend for older women to have higher thresholds than older men. The strongest evidence of a sex difference in arousability comes from the statistical modelling of arousal to low level fire cues (Hasofer & Bruck, 2004). Involving a total of 53 adults and using four different fire cues (crackling sound, shuffling sound, flickering light and smell) a statistically significant difference was found, with females showing a higher probability of waking to each cue than males. A trend was also noted for the mean response time to awakening to be shorter for females. A subsequent study involving smoke alarm signals and alcohol consumption also found similar significant sex differences (see Section 2.3.3 below).

One study has considered the effect that a dose of **hypnotics** (flurazepam 30 mg) may exert on arousal to pure tones (Johnson, Church, Seales & Rossiter, 1979). When the drug was exerting its maximum effect (some two to three hours after ingestion) the auditory threshold was approximately 30 dBA higher on drug nights compared to placebo nights. There are no published studies available on arousal thresholds to sounds that are not alarms after consuming other drugs, such as alcohol or marijuana. Studies testing responsiveness to smoke alarms after intake of different soporific substances, including alcohol, are described in the next section.

2.3 Awakenings with various alarm signals

Within the published literature there are a comparatively small number of studies considering arousal from sleep to an auditory emergency signal and most of these have involved the high frequency smoke alarm signal (continuous beeps rather than the T-3 unless otherwise specified). Several recent studies have compared this high frequency signal with a small range of different signals. These studies will all be reviewed here, in three categories;

- adults (where the studies have used samples of unimpaired adults or where any factors which may have impaired their arousal, such previous late nights or drinking, were not systematically manipulated);
- children;
- adults impaired by hypnotics, alcohol or hearing difficulties.

2.3.1 Adults

The first study to consider the issue of whether people would wake up to a smoke alarm was by Nober *et al.* (1981b). It was found that all 30 of the 18 to 29 year old male participants were able to wake up quickly (within 21 seconds) to a high frequency alarm presented in their homes at levels ranging from 55 to 85 dBA at the pillow. All the men even woke up when a 70 dBA signal was presented with a 53 dBA air conditioner noise in the background, although this took them up to 85 seconds. However, at the volume of a hallway alarm (55 dBA) only 70% of the men awoke when the air conditioner was on. In a subsequent, similar investigation 12 males were tested in a laboratory (Kahn, 1984) using smoke alarms of 44, 54 and 78 dBA at the pillow, against a background noise level of 44 dBA. The percentage who awoke were 25%, 50% and 100% respectively. Both studies clearly showed the detrimental effect of background noise (causing masking of the alarm signal) and suggested the importance of placing the smoke alarm within the bedroom itself to facilitate awakening.

A decade later Bruck and Horasan (1995) exposed 24 young adults (18-24 years) twice to a 60 dBA alarm. The percentage who awoke to both alarm presentations varied slightly according to the sleep stage at the time of signal presentation, with 87%, 75% and 75% awakening consistently across stage 4, stage 2 and REM sleep respectively. Latency to awakening was longer in stage 4 than in the other two stages (79 seconds compared to 20 seconds or less). It was found that those participants who slept through one or both signals were sleep deprived, due to significant exam-pressure sleep-restriction on the night before the experiment. Thus all the participants were not 'unimpaired' and this introduced a confound into the study. Studies of adolescent and young adult sleep patterns (Carskadon, Harvey & Dement, 1981) show that it is not at all unusual for individuals in this age group to have highly irregular sleep patterns, alternating nights of restricted sleep hours with nights of recovery sleep.

In a subsequent study, Bruck (1999) set out to more thoroughly investigate the waking likelihood of adults (across a wider age range) and children in the setting of their family home. A high frequency beeping alarm was set up in the hallway of selected homes such that it reached the pillows of both parents and children at 60 dBA. The 16 parents involved were aged from 30 to 59 years and the equipment was in their homes for five nights. Individuals who participated in the study were screened carefully and asked to abstain from any alcohol consumption and keep regular sleep/wake hours. They were told the smoke alarm would be activated on two of the five nights but did not know more specific details. It was always activated in the middle third of the night (1 to 4.30 am). Impressively, all parents awoke on both nights within 32 seconds.

In a recent study (Ashley, Du Bois, Klassen & Roby, 2005) 32 people with established normal hearing were tested in a sleep laboratory across the sleep stages of slow wave sleep, stage 2 and REM. A high frequency smoke alarm (3100 Hz) in the T-3 pattern was presented for two minutes at 75 dBA and it was found that 96% of participants awoke.

A large scale study involving 621 sleeping Disaster Protection trainees staying in a hotel (Nakano & Hagiwara, 2000), found that 90% evacuated within 120 seconds, where 74% reportedly awoke to the 50-53 dBA hotel emergency bell, a further 9% awoke to the subsequent 60-67 dBA siren, 2% to the final 48-55 dBA voice broadcast and 8% were awoken by others. The degree to which these young men were unimpaired is hard to judge as 193 reported that they had "drunk very much" during the evening, while 70 "got dead drunk". Nevertheless, the reported rate of responding to the signals is high.

To date the only controlled studies of the response of sleeping adults to different alarm signals are by Ball and Bruck (2004a, 2004b). These studies adapted the method of limits procedure, whereby a continuous signal was presented via a bedside speaker, starting at the whisper volume of 35 dBA and increasing in 5 dBA steps to a maximum of 95 dBA. Signals at each volume were presented for 30 seconds and moved on to a higher volume if there was no response. The main variables of interest were the time to the pressing of a bedside button and the decibel level when the person awoke (auditory arousal threshold, AAT). Three signals were presented each night during stage 4 sleep. The participants were self reported deep sleepers aged 18 to 25 years and a repeated measures design was used to minimise the variability due to individual differences. Their first study was a pilot study (n=8) to determine the relative effectiveness of three newly developed signals in waking up participants. In Section 2.1 above the development of two signals presenting the naturalistic house fire sounds and the female actor's voice (conveying emotion) was described (Phase 1 of Ball & Bruck, 2004b). The third signal tested in the pilot study (Phase 2) combined these two signals, continuously presenting each for 5 seconds (i.e., a signal shift). In this small sample it was found that the female voice signal was significantly more effective than either the naturalistic house fire sounds or the signal shift in waking the participants up.

In a further similar subsequent study, the comparative effectiveness of the female voice (300 to 2500 Hz), high pitch alarm (4000 to 5000 Hz) and a mixed frequency T-3 alarm signal (500 to 2500 Hz) were compared using 12 young adults (Ball & Bruck, 2004a). Based on the literature suggesting that signal significance was an important component in facilitating arousal, the researchers were expecting the human voice to be the most effective in waking participants up. However, it was found that the AATs for the female voice and the mixed T-3 alarm were similar and significantly lower than for the high pitch alarm (see Figure 2.2 in Section 2.3.3 below - sober condition).

A subsequent pilot study specifically compared responsiveness to a male voice with a female voice in a small sample of 10 young adult participants using a repeated measures design. (M. Ball & D.Bruck, 2005, unpublished data). The mean AAT for the female voice was 61.0 dBA (S.D.=18.1) and to the male voice, 52.5 dBA (18.3). Due to the small sample size this difference did not achieve statistical significance but six of the subjects found the male voice more alerting than the female voice at a lower volume, three equal and only one person was more easily alerted to the female voice. It was concluded that with an increased sample size it was likely that the male voice would yield significantly lower AATs than the female voice.

2.3.2 Children

The first study to suggest that children may not be effectively aroused by a smoke alarm assessed awakening using a hallway high pitched beeping alarm, which reached the pillow at 60 dBA (Bruck, 1999). Of the 20 children aged from 6 to 15 years, only 6% awoke on both nights when the alarm was presented. When the volume of the signal was increased to 89dBA at the pillow, the percentage who reliably awoke increased to 50% (Bruck & Bliss, 2000). However, the younger children (aged 6-10 years) were clearly more at risk, with only 29% within this age subset reliably awakening to 89 dBA. The researchers went on to consider the ability of this 6 to 10 year old age group to awaken to different signals, all presented at the volume of an alarm installed above their bed (89 dBA). Across several studies using a similar methodology Bruck and Ball

(2004) found that significantly fewer children awoke to the high frequency alarm compared to two voice alarms or the mixed frequency T-3 (see Table 2.3).[3]

Table 2.3. Number of children who awoke within different time categories to different alarm signals (from Bruck & Ball, 2004).

	N	Valid alarm present-ations[4]	0 - 30 sec	31 - 60 sec	60-180 sec	Awoke within 180 seconds but exact time not known[5]	**Did not wake**	% Total awake
mother's voice	20	19	15	4	0	0	**0**	100%
female voice	20	19	12	5	0	1	**1**	94%
high pitch alarm	14	28	10	1	4	1	**12**	57 %
mixed T-3	14	28	14	7	0	6	**1**	96%

The voice alarms consisted of either the child's own mother's voice (saying their name about once every 6 seconds) or a female actor's voice (as used in Ball & Bruck, 2004a and 2004b). Table 2.3 shows that significantly more children awoke to both the voice alarms and mixed T-3, compared to the high pitch alarm. In addition, the children awoke more promptly to the voice alarm and T-3 signal compared to the high pitch alarm and this difference was also significant.

2.3.3 Impaired adults

It is not surprising that the intake of hypnotics substantially reduces the ability to wake to a smoke alarm. Only one study has examined this effect experimentally (Johnson,

[3] The comparisons for this age group between the high frequency signal and the mixed T-3 were not repeated measures on the same children.
[4] i.e. the child reported retrospectively that they were asleep before the alarm was sounded
[5] This was due to technical difficulties with the wrist actigraphs.

Spinweber, Webb & Muzet, 1987) and found that 50% of the adults receiving the hypnotic, triazolam (0.25 or 0.5 mg), did not awaken to three one minute 78 dBA alarms, presented during deep sleep when the drug was exerting its maximum effect (2 hours post ingestion). This compared to 100% awakening with the placebo. With 35 million prescriptions for sleeping medications in the US in 2004, the arousal thresholds of many individuals are regularly substantially impaired, with the elderly disproportionately likely to take hypnotics (Medco Health Solutions 2005).

Despite the strong association between fire fatality and **alcohol** consumption (Sekizawa, 1991, Brennan 1998) the ability of intoxicated people to awaken to a smoke alarm has only recently been investigated. Arousal thresholds to three different alarm signals were explored in 12 young adults under three different levels of alcohol intoxication: sober, 0.05 Blood Alcohol Content (BAC) and 0.08 BAC (Ball & Bruck, 2004a).

Figure 2.2 shows that responsiveness to both the female voice and the mixed T-3 were very closely matched, and both signals aroused individuals at a mean sound intensity that was lower than the high pitched signal. It also shows the substantial increase in magnitude required for all signals when alcohol was administered. The research followed the modified method of limits procedure described earlier, so the time taken from the first 30 seconds, 35 dBA signal presentation to when the participant responded with a button press was a key dependent variable. Analyses showed that both the difference between the sounds and the difference between the three alcohol conditions were statistically significant (MANOVA).