Optimizing Fire Alarm Notification for High Risk Groups
Research Project

*Waking effectiveness of alarms (auditory, visual and tactile)
for adults who are hard of hearing*

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FIRE RESEARCH

FOREWORD

In April of 2006, the Foundation was awarded a Fire Prevention and Safety Grant by the US Fire Administration to study the effectiveness of alarms for emergency notification of high risk groups. The study's aim was to optimize the performance requirements for alarm and signaling systems to meet the needs of these groups. Elements of the study included: a risk assessment to estimate the potential impact in lives saved of changes in notification effectiveness of smoke alarms for these groups; quantifying the human behavior aspects of the problem; developing benchmark performance criteria for alarm and signaling systems; reviewing current and emerging technologies that address the performance criteria; and assessing the information developed in the above tasks to develop recommendations on notification technology for each target group and the overall impact for the general population. This report is one in a series of four that report on the on the results of the study.

The Research Foundation expresses gratitude to the report authors Dorothy Bruck and Ian Thomas of Victoria University, Australia; the Project Technical Panelists listed on the following page; and to the United States Fire Administration, the project sponsor.

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

Optimizing Fire Alarm Notification for High Risk Groups Research Project

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Waking effectiveness of alarms (auditory, visual and tactile) for adults who are hard of hearing

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1   Executive summary

As it has been shown that smoke alarms save lives (e.g. Ahrens, 2004) and that being asleep is a strong risk factor for fire fatality (e.g. Thomas and Brennan, 2002, Brennan 1998), the ability of different sections of the population to wake to their smoke alarm is an issue of importance.

Among the people at risk of not waking to an auditory smoke alarm are the more than 34.5 million people in the US who are hard of hearing. In some cases such people purchase alternative alerting devices which may send a visual signal (e.g. a strobe light) or a tactile signal which vibrates. Bed shakers and pillow shakers have become available for people with hearing impairment and may be used with an alarm clock or for emergency notification. Some specialist alerting devices allow the option of a loud low frequency sound.

Standards exist for the intensity of a strobe light for emergency notification (NFPA 72, 2002), with an intensity of 177 or 110 candela (cd) specified, depending on placement. However, several studies of their efficacy in alerting sleepers suggest that only about a third of hard of hearing people or people with normal hearing will awaken to strobe lights of similar intensities (Bowman et al. 1995: Du Bois et al. 2005).

For bed shakers UL 1971 (1991) provides a standard but the specifications relate to a shaker of different shape to most shakers currently sold. The bed shakers tested in sleep studies report waking rates of 70-100% when using shakers at "off the shelf" intensities (Underwriters Laboratories, 1991; Murphy et al. 1995; Du Bois et al. 2005).
The British Standard, BS 5446-3 (2005) relates to a smoke alarm "kit" for people with hearing impairment which combines the normal UK smoke alarm with a vibration pad (a bed shaker) and a flashing light. The minimum intensity specified for the flashing light is quite low (15 cd). For the bed shaker frequency ranges, pulse patterns and displacement specifications are provided, along with a standardized testing procedure. However, there are no published sleep studies which test the specified kit or report the intensity of the bed shakers as compared to the BS5446-3.

This study set out to test the waking effectiveness of several different auditory signals, a bed shaker, a pillow shaker and a strobe light in a sample of hard of hearing people. A range of different intensity levels were tested for each signal. Each device was tested separately.

Participants were 38 volunteers aged 18-77 years (16 males, 22 females) with an average hearing loss of 25-70 dB in both ears (i.e. mild to moderately severe hearing loss). No deaf individuals participated. Each participant was exposed to a range of signals across two non-consecutive nights during slow wave sleep (the deeper part of sleep, stages 3 and 4). Six signals were tested:

- 400 Hz square wave signal in T-3 pulse
- 520 Hz square wave signal in T-3 pulse[1]
- 3100 Hz pure tone in T-3 pulse (the current smoke alarm)
- Bed shaker (under mattress) in T-3 pulse
- Pillow shaker in T-3 pulse
- Strobe light in T-3 pulse (modified)

The first two signals used in the sleep study (as listed above) were chosen from a larger set of audible sounds that were used in the awake portion of the study. These first two audible signals had the lowest average hearing threshold from a set of eight different auditory signals. Each signal was presented for 30 seconds, followed by a short period without a signal (30 -70 seconds). After this pause the signal was presented at a higher intensity level and this continued until a range of intensities had been presented, or the participant awoke.

In addition, a questionnaire was administered to all volunteers for the study (n=44). This asked a variety of questions about their hearing, use of specialised alerting devices and their confidence in their ability to hear different alerting sounds in their home (e.g. telephone, fire alarm) both during the day and night.

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[1] This signal is that same as the one referred to in previous studies as the "mixed T-3" (Bruck et al. 2004; Ball and Bruck 2004; Bruck et al. 2006). Square waves have, in addition to their fundamental frequency, additional peaks at the 3rd, 5th, 7th etc harmonics.

The main conclusions from this study are:

1. Under the testing conditions a 520 Hz square wave T-3 sound was the single most effective signal, awakening 92% of hard of hearing participants when presented at or below 75 dBA for 30 seconds and awakening 100% at 95 dBA. Both the 520 Hz square wave and the 400 Hz square wave were significantly more effective than the 3100 Hz pure tone T-3 sound, which awoke 56% at or below 75 dBA. In addition the 520 Hz square wave signal yielded the lowest hearing threshold when awake for this sample of people who were hard of hearing, from a set of eight alternative sounds with a range of pitch and patterns. [2]

2. Under the testing conditions the bed shaker and pillow shaker devices, presented alone, awoke 80-83% of the hard of hearing participants at the intensity level as purchased (vibrating in intermittent pulses).

3. Those hard of hearing participants who were aged 60 years or more were less likely to awaken to the bed shaker than those aged below 60 years. No age group differences were found for any other signal.

4. Strobe lights, presented alone, were not an effective means of waking this population, with only 27% waking to the lowest strobe light intensity, which was more intense than that required by the standard (NFPA 72, 2002).[3]

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[2] The efficacy of the 520 Hz square wave signal in arousing sleepers has now been demonstrated in children, sober young adults, alcohol intoxicated young adults (two studies), older adults and hard of hearing people. Furthermore, in all these studies the high pitched alarm has been found to be the least effective of the auditory alternatives tested, for waking people up.

[3] This finding is consistent with the other two studies that have controlled for stage of sleep and tested the effectiveness of strobe lights in hard of hearing or normal hearing samples.

5. There was tentative evidence that people may respond differently to different types of signals, suggesting that a bedroom alarm "kit" that combined two types of sensory signals (i.e. an auditory signal plus a tactile signal) may be more effective than one signal.

6. The results in this study are likely to be overestimations of the proportion of the hard of hearing population who may awaken to these signals in an unprimed, unscreened population, especially from deep sleep. Thus extrapolations of absolute intensities and percentages awoken in the study to the field should be made with caution.

7. It was found that, when a signal was presented at a level that caused awakening, most people awoke to the signal within the first 10 seconds of the signal being on. Thus it seems highly probable that a T-3 signal that is alternatively ON for about 10-15 seconds and OFF for a certain period of time (possibly of the same duration) will be more effective than a continuous sounding T-3 signal.

8. Questionnaire responses indicated a high level of misplaced complacency among people who are hard of hearing in terms of their need for specialist alerting devices. In view of this, and the fact that many people are not aware of their hearing loss, it is desirable that any standard audible smoke alarm for the general population emit a signal that maximises the chances of awakening for hard of hearing people (provided such a signal presents no increased risk to other sections of the population).

Recommendations:

1. The technical feasibility of replacing the current high frequency smoke alarm T-3 signal with a low frequency square wave T-3 signal (with a fundamental

frequency of 520 Hz or thereabouts[4]) for the entire population should be investigated as a matter of priority.

2.   A suitable ON duration of such a T-3 signal appears likely to be in the range of 10-15 seconds, with the OFF duration tentatively suggested to be of similar duration but further research is required to determine this.

3.   For this population of people with mild to moderately severe hearing loss the single best emergency alerting device is a low frequency square wave auditory signal and this is superior to bed shakers, pillow shakers and strobe lights, presented alone. Ideally this square wave signal should be as loud as possible. There is tentative evidence that combining a low frequency square wave with a tactile device may provide additional waking effectiveness.

4.   Any recommendations for the use of strobe lights, presented alone, as an emergency alarm to awaken sleepers who are hard of hearing or of normal hearing should be withdrawn as soon as possible.[5]

5.   Further study should be undertaken with people with hearing loss ranging from moderate to profound (i.e. including deaf people) to determine the best signals, or combination of signals, that will reliably awaken this population from deep sleep. This should include bed shakers, pillow shakers, low frequency square waves (beneficial for those with residual hearing) and could include strobe lights. In such research it would also be of interest to test bed shakers (vibrating in intermittent pulses) in an under-the-pillow placement.

6.   Research on the efficacy of a range of different signals and signal combinations in different populations (e.g. with and without hearing loss)

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[4] We are currently undertaking a study with unimpaired young adults which will compare arousal to a 520 Hz square wave with other square wave signals with fundamental frequencies between 520 Hz and 2000 Hz.

[5] This recommendation should not be misinterpreted to apply to people who are awake or to deaf people. Neither of these conditions were tested in this study or the companion report on the alcohol impaired (Bruck, Ball and Thomas, 2007).

should also be conducted in a large number of home environments where the participants were not primed to expect a signal during the night and unscreened for factors such as medication or prior alcohol consumption.

7. There should be further investigation of an appropriate means of standardising the measurement of the intensity of bed and pillow shakers and this should inform a new standard.

2   Review of the Literature

People who are profoundly deaf are typically very aware of their inability to respond to auditory cues such as the doorbell, telephone and alarms. They may install specialist non-auditory devices to facilitate such communications if their hearing aids provide insufficient amplification. However, many people whose hearing loss is less severe (the "hard of hearing" people) may not feel a strong need for such specialist devices, especially if their hearing aids are effective in increasing their functional hearing of signals. In such cases the major problem with hearing auditory alerting devices may be when they take their hearing aids out, as people do when they go to bed. Furthermore, people with mild or moderate hearing loss may not be advised by hearing health care professionals about what alerting technology they might need to obtain or whether they would be unlikely to wake up to smoke or carbon monoxide alarms.

An additional problem is that the most common known type of hearing loss is associated with advancing age (presbycusis) and especially affects the ability to hear high frequency tones (such as a domestic smoke alarm). Older adults with such presbycusis are particularly at risk for not hearing their smoke alarms, especially when asleep. Further, they may be unlikely to install any alternative alarms as they may be able to hear their lower frequency signals such as the doorbell and telephone without major problems. Indeed, they may be unaware of the extent of their high frequency hearing loss. Even if they hear their smoke alarms when awake the lower arousal thresholds associated with sleep may mean that the high pitched beeping does not arouse them. This places them at a higher risk of dying in a fire.

2.1 Fire fatality, smoke alarms, and sleep

In order for a smoke alarm to save lives people must be capable of hearing the alarm both during the day and at night in bed. Statistical studies of the predicted number of lives saved due to smoke alarms suggest that they are largely effective (Ahrens, 2004; Norris, 2004). However, 20.3% of US home fire deaths occurred in homes where a smoke alarm was present and operated (Ahrens, 2004) and this means some 770 people die annually in the US despite their smoke alarm (Fahy and Molis, 2004). Some of these fatalities arise from scenarios where smoke alarms could not play a role (e.g., ignition of clothing or children hiding in fear) or where the occupants were too injured or

disabled to escape in time. In one and two family homes where a smoke alarm was present 59% of the fire fatalities were not in the room of fire origin (Ahrens, 2004) suggesting the importance of adequate notification to escape.

In some cases a smoke alarm may not arouse the sleeping occupants in time to escape and a lack of response, or a delayed response clearly increases the chance of dying in a fire (Thomas and Brennan, 2004). An analysis of coronial reports of fire victims in Australia (Brennan, 1998) breaks down information on whether the victim was awake or asleep by age. Across all the fatalities (n=150), two thirds of the victims were asleep. Between ages 5-64 years victims were much more likely to be asleep than awake at the time of the fire. This difference was less for very young and very old victims. Not surprisingly the vast majority (86%) of victims of night fires (8pm to 8am) were asleep. However, 31% of day fire fatalities were also asleep. Clearly being asleep is a more accurate indicator of risk than time of day, emphasizing the importance of sleeping occupants awakening in sufficient time to escape.

2.2 Prevalence and age distribution of the hard of hearing

Self report data is one way of answering the question of how many people in the US, across different age groups, may be hard of hearing. Mitchell (2005) uses the annual National Health Interview Survey (NHIS) data to estimate how many people in the US are deaf or hard of hearing. The NHIS survey includes the following question:

> *"Which statement best describes your hearing (without a hearing aid): good, a little trouble, a lot of trouble, or deaf?"* (in 2003, Question ACN 420).

Mitchell (2005) provides an independent analysis of this NHIS public-use data for 1997-2003, and reports the data separately for the "deaf", "a lot of trouble" hearing and "a little" trouble hearing. From their data the percentages for certain response categories were given as a function of age and are shown in the second column in Table 2.1. For the purposes of the current report on hard of hearing adults it was considered most appropriate to combine the two self-report hearing descriptive categories and omit the "deaf" category.   From the table it can be seen that some 34.5 million people aged over 15 years in the US may be hard of hearing. Somewhat consistent with the data in Table 2.1 are Cruickshanks et al. (1998) results, based on a large epidemiological study of hearing loss in the US, which found that 33.7% of 48-92 year olds self-reported hearing loss. However, their audiological testing revealed this to be an underestimation, with

46% actually having a hearing loss.[6] Thus it seems likely that the 34.5 million is an underestimation. Those with noise-induced hearing loss at higher frequencies (which is likely to affect their ability to wake up to high-frequency smoke alarms) are especially likely to be unaware of their hearing loss because their speech discrimination may not be affected.

Table 2.1: Age characteristics and US population numbers who may be hard of hearing.

Age group (yrs)	% of that age group reporting "a lot" or "a little" trouble hearing	US population in that age group*	US population reporting "a lot" or "a little" trouble hearing
15-44	7.8%	125.0 million	9.7 million
45-64	18.8%	61.8 million	11.6 million
65+	37.9%	34.8 million	13.2 million
Total			34.5 million

* US Census Bureau data, Census 2000 (Table DP-1)

Given the current age profile of the US population, and the fact that the percentage of the population reporting some trouble with hearing doubles from the age group 45-64 years to the over 65 year olds, the number of people in the US who are hard of hearing will rise dramatically over the next few decades.

The following two figures (Figures 2.1 and 2.2), using the data from Cruickshanks et al. (1998) study, show the decibel threshold level of the population in different age groups. Each point represents the minimum hearing threshold of the poorest hearing third of the population within each age and sex grouping (that is, the hearing threshold in decibels that was one standard deviation above the mean[7]). This value was chosen for illustration purposes as it approximates the minimum decibel threshold for those who self-report hearing loss (given that 33.7% across the age groups shown reported some

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[6] Defined as a pure tone average of thresholds at 500, 1000, 2000 and 4000 Hz greater than 25 dBA of hearing loss in the worst ear.

[7] In other words the figures show the decibel threshold level of 66.6% of the US population.

hearing loss in the same study). It can be seen from Figure 2.2 that the third of the 80-92 year old male population with the poorest hearing would need a minimum volume of 80 decibels to hear a 3000 Hz sound. In contrast they would only need a minimum volume of 55 dBA to hear a 500 Hz sound. This data demonstrates that the requirement of a minimum of 75 dBA level at the pillow (NFPA 72) for the high pitched smoke alarm signal is problematic for many sleeping older adults. In fact, many males aged over 60 are at risk of not hearing the 75 dBA high pitched sound even when awake.
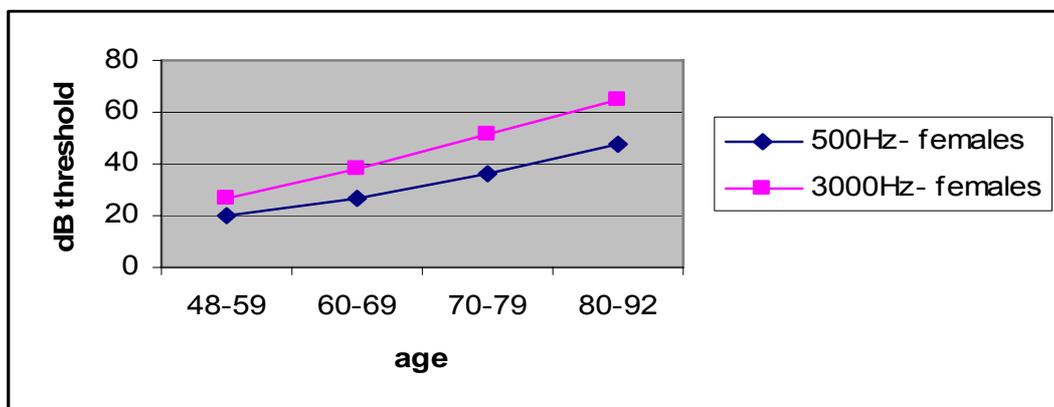
Figure 2.1: Hearing thresholds when awake for the third of the female population with the poorest hearing as a function of frequency and age (data from Cruickshanks et al. 1998)
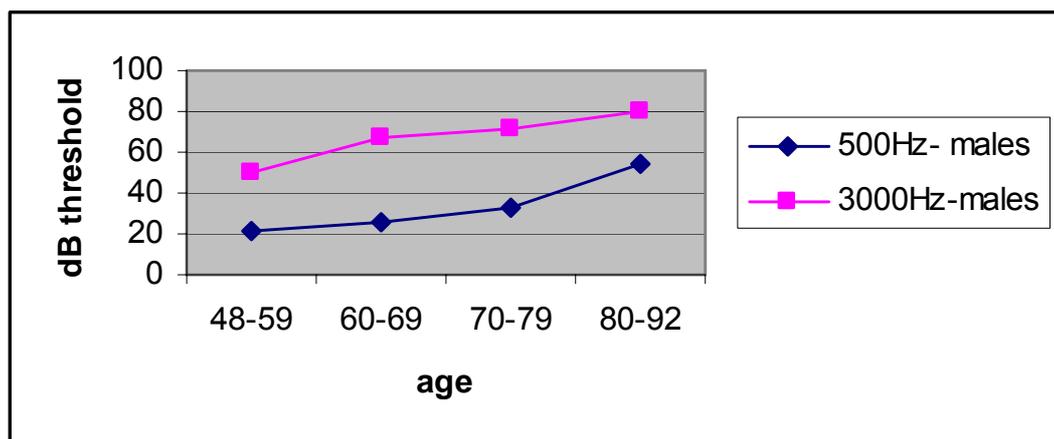
Figure 2.2: Hearing thresholds when awake for the third of the male population with the poorest hearing as a function of frequency and age (data from Cruickshanks et al. 1998)

Devices designed to awaken people who are hearing impaired typically incorporate one or more of the following types of signals

- auditory signal that is loud and of a low frequency

- tactile device such as a bed shaker or pillow shaker
- flashing visual device, such as a strobe light.

The following sections review the available literature on the effectiveness of such signals and discuss any standards that may apply.

2.3 Auditory emergency signals, sleep and the hard of hearing

Some alerting devices specially designed for people who are hard of hearing allow the option of a loud auditory signal. Our testing has shown these are typically a mixed signal between 400 Hz and 2,500 Hz. However, only one study has been performed where sleep stages were controlled and percentage waking was investigated for sounds of different frequencies in relation to hard of hearing participants. In the study by Du Bois, Ashley, Klassen and Roby (2005) 45 hard of hearing participants[8] were exposed to both a standard audible alarm of 3100 Hz and a 450 Hz alarm[9], both presented at "less than 75 dB" for two minutes. Stage of sleep was controlled to be either stage 2, REM or slow wave sleep (SWS) at the time of signal presentation.[10] Only 57% of the hard of hearing participants awoke to the 3100 Hz signal while 92% awoke to the 450 Hz signal.

Previous research has shown that a signal called the "mixed T-3" (a 520 Hz square wave with a T-3 pulse) has a lower auditory arousal threshold in older adults (screened to exclude any who were below one standard deviation on the hearing screening test for their age) compared to a pure tone of about the same dominant frequency (Bruck, Thomas and Kritikos, 2006; Bruck and Thomas 2007). That study of 45 older adults also found that the 520 Hz square wave performed significantly better than a high pitched signal (3000 Hz), with the median auditory arousal thresholds of each differing by 20 dBA. In addition, a voice signal was found to be comparatively ineffective with sleeping

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[8] The criteria was that their "average hearing ability fell between 20 dB - 90 dB over the range of 250 Hz-8000 Hz." Whether this was for both ears, the better ear or the worst ear was not stated.

[9] Presumably a pure tone signal but this was not stated. It is also unclear whether the signals were in the Temporal Three pattern or not.

[10] However, whether the number of presentations in each stage for each signal was the same was not stated.

older adults (Bruck et al. 2006; Bruck and Thomas, 2007). Interestingly the same 520 Hz square wave signal has also been found to be more effective at waking sleeping children (Bruck, Reid, Kouzma and Ball 2004), and sober and alcohol intoxicated young adults (Ball and Bruck, 2004; Bruck, Thomas and Ball, 2007)

The operation of residential auditory fire alarms and smoke alarms are regulated around the developed world by a range of standards and regulations. A standard that is widely implemented requires the smoke alarm volume to be at least 85 dBA when measured at a distance of 10ft (~3 metres) under specified conditions (in the US UL 217, in the UK BS 5446-1; in Australia AS 2362.22). The US National Fire Protection Association (NFPA) requirements for the notification signal for fire alarms (including smoke alarms) in sleeping areas is the greater of (i) 15 dBA above the average ambient sound level, (ii) 5 dBA above the maximum sound level having a duration above 60 seconds and (iii) 75 dBA measured at the pillow level (NFPA 72, 58, 7.4.4.1). In most residences the 75 dBA minimum sound level at the pillow would apply. In Australia the 75 dBA minimum at the pillow applies to fire alarm systems for buildings such as hotels /motels (AS 1670.4, 4.3.3, and smoke alarms within such systems AS 1670.6, 2.2.1). Smoke alarm signals become more attenuated with any increase in the complexity of the path of travel (Lee, 2005). Thus hallway alarms may not result in 75 dBA being received at the pillow. In the US and Australia smoke detectors on the market now emit the Temporal 3 (T-3) pattern. The T-3 is a temporal pattern of a signal being on and off for 0.5 seconds three times in succession followed by a 1.5 second pause. The T-3 signal is set out in ISO 8201 and is now required as the emergency fire evacuation signal by many regulatory authorities. The ISO does not specify the frequency of the T-3, apparently so that the signal can be matched to any background noise to optimize its perception (Proulx and Laroche, 2003). The signal emitted by most current smoke alarms is around 3,100 Hz or more (Lee, 2005).

2.4 Non-auditory emergency signals and sleep

Tactile alarms - Bed and Pillow Shakers

There are currently a number of products on the market that aim to awaken sleepers (normally hard of hearing and deaf people) using a tactile signal in the form of a small device that vibrates. Investigation of a range of tactile products has determined that

some are marketed for placement under either the mattress or the pillow (termed bed shakers here) while others are marketed for placement only under the pillow. Pilot testing of a sample of products found that the bed shakers emit a vibration that is of a lower frequency and higher amplitude than the pillow shakers and the voltage of the former is larger. The two types may be similar in terms of size, shape and the low level sound volume associated with the spinning weight inside the device. Three studies report responsiveness during sleep to a tactile alarm.

1. In 1991 Underwriters Laboratory published a report on emergency signalling devices for the hearing impaired and this included a study using bed vibrators. A cylindrical vibration device with a cylinder displacement of 1/8 inch and a vibration of 100 Hz was placed either under the pillow or under the mattress (under centre of the torso position) and activated between 1 and 4 am. Assessment of, and control for, sleep stage was not conducted. Testing on 20 legally deaf adults found 95% awoke to a four minute presentation of the vibrating device, and the rate was the same for either the under pillow or under mattress placement. Testing was also conducted on 77 deaf 10 to 19 year olds, with the awakening rate in different age groups varying from 77% to 100%.

2. Murphy, Alloway, La Marche et al. (1995) studied the effectiveness of an under the mattress bed shaker using an off-the-shelf model, L'il Ben SS12. Testing involved 11 hard of hearing adults aged 20-76 years, with hearing loss ranging from slight to profound, and 16 young adult university students with self-reported normal hearing who wore ear plugs. Ninety two percent of the normal hearing group woke quickly (within one minute) to the bed shaker from REM sleep and 76% awoke quickly from slow wave sleep (SWS). Waking response rates for the hard of hearing subjects were similar (87% awoke from REM sleep and 70% from SWS), however, awakenings were often slower in this group, with 19% requiring more than a minute to wake up.

3. Du Bois et al. (2005) found that a continuous bed shaker (which we understand was placed under the mattress) was differentially effective with different populations; 92% effective for hearing able adults (n=34), 82% for those with partial hearing (n=45) and 93% for deaf participants (n=32). Bed shakers with an intermittent pulse were 100% effective for all hearing levels, even from deep sleep. It was stated that the bed shakers were 0.14-0.19 RSS. However, RSS (Received Signal Strength) is not a unit mentioned in the UL or BS standards for

tactile devices and any measurement details and other specifications were not given.   It is understood (M. Klassen, personal communication, 2006) that the intermittent pulse was in a T-3 signal. Sleep stages were measured in this study and signals presented in documented sleep stages (Stage 3/4, REM, and stage 2), however, it was not clear whether each signal was presented an equal number of times in each sleep stage.

The UL 1971 standard for tactile devices for emergency awakening requires a minimum amplitude of 1/8th inch (3.2 mm) but no information is provided of the conditions under which this should be assessed. It also specifies a voltage range of 8 -17.5 volts. It should be noted that the UL (1991) testing and the UL 1971 specifications relate to a cylindrical shaker that is of a different shape to most shakers on the market (which are circular), with the illustration in the UL (1991) research report giving the dimensions of 4½ inches by $1^3/_8$ inches and notes a frequency of 100 Hz.[11]   The intensity of tactile signals is not covered in the National Fire Alarm Code, NFPA 72. To our knowledge no US standards apply to whether the signal is presented in a pulse or continuous form. In 2005 a British Standard (BS 5446-3) was published which contained specifications for smoke alarm 'kits' for deaf and hard of hearing people. This standard requires that any smoke alarm kit for deaf or hard of hearing people incorporates a standard UK auditory smoke alarm as well a combination of a vibration pad (for placement under the bed or mattress) and flashing light. The specifications for the vibration frequency, pulse pattern and vibration intensity are set out in section 5.4.2 of the British Standard. This states that the pad shall vibrate at a frequency within the range 25 Hz to 150 Hz and shall have a pulse pattern with an "on" period of 2 ± 1 second and an "off" period of 2 ± 1.5 seconds, after a delay of not more than 3 seconds. Specifications for the vertical r.m.s. (root mean squared) displacement are also provided (5.4.2.c.), specifying displacement levels of not less than 0.05 mm when on.

Strobe lights

Over the years strobe lights have been considered an option for the emergency awakening of people with hearing impairment. However, the literature is quite variable

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[11] This is different to the two shakers purchased in the US and sent to the authors and different in shape to the bed and pillow shakers, purchased in Australia, used in the current study. See Appendix A for further details.

in terms of how effective they may be. Four published studies have considered the waking effectiveness of the strobe light.

1. Nober et al. (1990) first tested people when awake to determine which colour light (white, red, yellow and blue) was reported as the brightest. With eyes closed the college students reported that the white light was subjectively the brightest. They then tested 48 deaf and 30 normal hearing subjects while asleep using either an industrial strobe (rated as 100 candela, 75 flashes/min, yielding 3.3 lumen-sec/m at the pillow which was 10 feet way), a household strobe (25 Watt, yielding 1.51 lumen-sec/m at the pillow) and a 100 Watt, 5 Hz flashing light bulb. Sleep stage was not assessed or controlled. The two strobes performed equally well, while the white light bulb proved much less effective. Ninety percent of the deaf participants awoke to the strobes, compared to 63% of the normal hearing.

2. The Underwriters Laboratory (1991) study reported above in connection with bed shakers also tested strobe lights. They reported that a 110 cd strobe light presented for four minutes was 100% effective at awakening 22 deaf adults (aged 20-65 years), 91% effective for 53 deaf High School students and 86% effective for 12 deaf Junior High students. The signal was delivered between 1 and 4 am and sleep stage was not assessed or controlled.

3. Bowman, Jamieson and Ogilvie (1995) controlled for sleep stage and reported the strobe light intensity at the pillow. They found that less than 30% of their 13 normal hearing female participants awoke from deep sleep to the highest intensity strobe they tested for five minutes. They claim that the strobe lights used in their study (and placed just 75 cm from the pillow) met or exceeded the levels provided by devices that were widely available and met the American Disabilities Act recommendation (75 cd). However, it is difficult to determine whether their highest intensity strobe would have delivered a more intense signal at the pillow than that which would be expected from a strobe that met the NFPA 72 standard (177 cd/110 cd) and placed as suggested in the standard. They reported a light level of 19.9 Lux at the pillow.

4. In the study by Du Bois et al. (2005) where sleep stages were also recorded, the available information reports that a 110 cd, 1 Hz strobe light was used and its waking effectiveness was 57% for the deaf participants, 34% for those who were hard of hearing and 32% for the hearing subjects across the three

different sleep stages of SWS, stage 2 and REM. Overall, a trend for decreased awakenings with strobes from deep sleep (SWS) was noted but percentages were not reported. Details of the strobe's placement or intensity at the pillow were not given.

Thus the literature does not tell us what light intensity of the strobe at the pillow (if any) may effectively awaken people during the deepest part of sleep. The literature also suggests that deaf people may be more sensitive to the strobe lights while asleep than normal hearing people. The two studies where sleep stages were assesses showed strobes were much less effective than the earlier studies without sleep assessment and control.

The NFPA 72 standard requires that the strobe light for the hearing impaired flash at a rate between 1 and 2 Hz and have an intensity of 177 candela (cd) or 110 cd (the former if the signal is placed within 24 inches of the ceiling, the latter if more than this from the ceiling) (NFPA 72, 2002). These intensities do not relate to the received intensity at the pillow, nor is there any guidance on placement of strobes in relation to the pillow. The UL 1971 details specific light dispersions (as percentages) at different viewing angles, but gives no guidance on the required intensity ratings for strobes.

In the smoke alarm kit specified in British Standard BS 5446-3 the visual alarm device is required to be white and of an effective light intensity of not less than 15 cd (section 5.3.2 of the standard) at a dispersion angle of 0 degrees. A table of minimum effective intensity values for vertical and horizontal dispersion angles is provided. The light requires a flash rate of 30 to 130 flashes per minute after a delay of not more than 3 seconds.

3   Aims, Research Questions and Design Issues

Research Questions

This study provided data on auditory, visual and tactile signals for their ability to alert people with mild to moderately severe hearing impairment (termed hard of hearing in this report) in residential settings. The research questions addressed form three separate phases.

Phase 1 (AWAKE)

1. What are the pitches and patterns of the two auditory T-3 signals (labelled X and Y) with the lowest auditory thresholds for this population when awake?

Signals X and Y were determined from a range of eight possibilities. The general description of the frequencies and patterns of these signals are shown below.

Auditory signals used in AWAKE phase
400 Hz square wave - T-3 pulse
520 Hz square wave - T-3 pulse
White noise - T-3 pulse
400 - 1600 Hz rising whoop - T-3 pulse
400 – 800 Hz rising whoop - T-3 pulse
3 pure tones; 400, 800 1600 Hz - T-3 pulse
500 Hz pure tone - T-3 pulse
3100 Hz pure tone - T-3 pulse

The rationale for the first seven signals was that they were either at a relatively low frequency and/or contained a mixture of frequencies in the low and medium frequency range. The current smoke alarm signal was also included in the AWAKE testing for comparative purposes.

Phase 2 (ASLEEP)

1. How do signals X and Y above compare to the current smoke alarm signal in terms of effective arousal from sleep?

2. Are bed shakers and pillow shakers an effective means of waking this population from deep sleep? If so, what minimum intensities are required for bed shakers and pillow shakers under the testing conditions of a pulsing signal in a Temporal 3 (T-3) pattern?

3. Do strobe lights provide an effective means of waking up from deep sleep for people who are hard of hearing? Is the NFPA 72 standard for the intensity of strobe lights (177 cd/110cd) high enough to effectively awaken this population under the testing conditions (using a T-3 pattern), or are strobes of a higher intensity required for awakening?

4. Does signal offset promote awakening (as well as signal onset)? If so, what are the implications of this for the temporal pattern of signal presentation?

5. How does the waking effectiveness of all of the above signals compare to the 3100 Hz pure tone T-3 (the current smoke alarm signal) for the hard of hearing?

6. How do each of the signals perform with the hard of hearing population in comparison to the applicable standard, or in the case of the tactile devices, to the intensity level as purchased?

7. How do the auditory signals, shakers and strobe lights compare in terms of waking effectiveness?

8. Is there a relationship between auditory thresholds when awake and asleep for this population?

9. Are there any sex differences in arousal thresholds to the different signals?

10. Are there any differences in arousal thresholds for different signals in those aged below 60 and those aged 60 years or more?

11. Do different people wake more effectively to different signals (e.g. auditory or tactile)?

12. Are there any differences across the different signals in the time taken between EEG wakefulness and responding behaviourally as instructed (pressing a bedside button)?

The signals tested during the ASLEEP phase are as follows:

Device
Auditory T-3 signal (X)
Auditory T-3 signal (Y)
3100 Hz pure tone T-3 auditory signal (current alarm)
Bed shaker- under mattress – T-3 pulse
Pillow shaker – T-3 pulse
Strobe light- T-3 pulse (modified)

An investigation of how the strobe lights used in the ASLEEP phase compared to other strobes available on the US market was conducted and this comparison is presented in Appendix B.

In this study all devices presented a pulsating signal in the same form, as far as possible, as the T-3 signal, as set out in ISO 8201. The decision to only test a pulse pattern was based on several factors:

- the desire of the fire safety community to make the T-3 the recognised evacuation signal,
- to make the fire notification signals different from other signals (e.g. a telephone, doorbell) across visual, auditory and tactile modalities
- the report of the greater effectiveness of an intermittent bed shaker compared to a continuous shaker (Du Bois et al, 2005) and,
- the knowledge from cognitive psychology that sensory adaptation is more likely to occur with an ongoing unchanging signal than one with pattern variations. Sensory adaptation will reduce responsiveness because people are especially sensitive to stimuli change.

Phase 3 (Alerting Devices Questionnaire)

1. What kind of provision do individuals who are hard of hearing make in terms of products in their homes for emergency notification (i.e. to a fire) and what are the barriers to purchasing such specialist devices?

2. Does this provision depend on their age, functional hearing level, use of hearing aids, history of hearing impairment and/or living arrangements?

3. How confident are they about their ability to hear various domestic alerting devices, including alarms, during the day and night?

4   Method

4.1 Participants

A total of 38 participants were involved in both the AWAKE and ASLEEP phases (16 male, 22 female, mean age = 54.4, SD = 16.0, age range = 18 -77 years). Different numbers of participants completed different signals with the number for each signal varying from 30 to 37.[12] This was due to four people dropping out after night 1, some people failing to return to slow wave sleep after one or two signals were presented (and being unwilling to complete another night) or technical difficulties. Forty four participants (18M, 26F, mean age = 56.4, SD = 17.4) were initially recruited who met the selection criteria and responses to the Alerting Devices Questionnaire are presented for this sample. (Six of these people chose not to proceed to the ASLEEP phase of the study.)

People were recruited who met the following criteria:

- Met the hearing screening criteria test (see below).

- Report that they do not regularly take medication that affects their sleep,[13] do not have a sleep disorder, and do not normally have difficulty falling asleep.

- Report that they do not have any major physical or neurological conditions that may affect their ability to perceive or respond to a visual, tactile or auditory signal (apart from hearing impairment).

- Be aged between 18 and 80 years.

- Give informed consent.

Recruitment   Participants were obtained using a variety of recruitment methods. Almost half of the participants were recruited through the following; friends and family contacts, social groups (especially for older people), organisations for the hearing impaired (including retail outlets for specialist alerting devices), offices of audiologists and articles in magazines for people over 50 years of age. After these methods were exhausted it was decided to place an advertisement for two weeks in 26 local papers

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[12] Specific numbers for each signal are provided in Table 5.3.

[13] Participants taking medications that did not affect their sleep were allowed to participate. Carter (2003) was consulted on this issue.

(delivered free to people's homes). The advertisement is shown in Appendix C. This produced sufficient volunteers.

Hearing loss criteria   All participants had a hearing loss of greater than or equal to 25 dB and less than or equal to 70 dB in both ears, with the hearing loss being based on the pure tone average of thresholds at 500, 1000, 2000 and 4000 Hz. This is similar the definition used by Cruickshanks et al.(1998) except their definition was based on the worst ear. The U.S. Health and Nutrition Examination Survey used the average of the same frequencies and based their data on the better ear (cited in Cruickshanks et al. 1998). The range of decibel loss (25-70 dB) means the participants in the study could be described as having mild to moderately severe hearing loss. (See Appendix D.1 for more information on the effects of various levels of hearing loss.)

The definition chosen for the study was based on functional relevance, with the 4000 Hz tone included as smoke alarms emit a signal of 3000 Hz or more, and the worst ear chosen as people could sleep on their better ear and thus be much less able to hear any emergency signal. As the focus of the study was on hard of hearing people who would theoretically be capable of waking to auditory alarms, those volunteers with severe or profound hearing loss (threshold average >71 dBA) were not eligible for this study. In practice most participants wore a hearing aid (see Phase 3 results, Section 5.10) or had been told by a professional that their level of hearing loss was such that they would benefit from a hearing aid. Verbal communication was still possible with participants not wearing a hearing aid.

A summary of the sample's thresholds for each ear and each frequency is provided in Table 4.1. The hearing thresholds for all participants across both ears, as given by the hearing screening test, is set out in Appendix D.2. Appendix D.3 considers the extent to which the age distribution of the study sample reflects the age distribution of hard of hearing people in the US, with the match across the different age groups being reasonably close.

Table 4.1: Descriptive statistics for the hearing screening test thresholds (dB) at four different frequencies (Hz) for the sample involved in the AWAKE and ASLEEP phases of the study (n=38), where L=Left ear and R= Right ear.

	Mean (SD)	Median	Range
L 500	37.3 (15.1)	40	10-65
L1000	37.9 (17.0)	40	10-65
L2000	41.5 (16.4)	40	10-70
L4000	50.5 (18.1)	50	15-90
R500	38.2 (16.5)	35	15-80
R1000	40.9 (17.7)	35	10-80
R2000	42.9 (17.0)	40	15-85
R4000	49.1 (16.2)	50	20-85

Payment: Compensation for inconvenience was $80 AUS per night with a $75 completion bonus to be paid after both nights were completed. The Information Sheet informing potential participants about the study is contained in Appendix E.

4.2 Apparatus

Hearing loss screening: An audiometer (Endomed SA 201/2 #13355) with specialised headphones which allowed field testing in quiet environments was used (thus a sound chamber was not required).

Signal delivery: For both the AWAKE and ASLEEP phases this was achieved via a specialised computer program that delivered each signal for a 30 second period at a nominated starting intensity and increased the signal level after a pause of a set duration. The program automatically stored the behavioural response times and the signal levels presented.

Auditory signals: In the AWAKE phase, the following eight signals were presented, all in a T-3 pulse.

1. 400 Hz square wave
2. 520 Hz square wave[14]
3. White noise
4. 400 - 1600 Hz rising whoop (across 0.5 seconds)
5. 400 – 800 Hz rising whoop (across 0.5 seconds)
6. 3 pure tones; 400, 800, 1600 Hz (each of 0.5 second duration)
7. 500 Hz pure tone
8. 3100 Hz pure tone - current smoke alarm

In the ASLEEP phase the two auditory signals found to have the lowest auditory threshold in the AWAKE phase, plus the 3100 Hz pure tone, were evaluated during sleep. Three auditory signals were evaluated during sleep and presented initially at 55 dBA increasing in 10 dBA increments until 95 dBA. Appendix F contains the spectral profiles of sounds 1, 2, and 8 (see above) as assessed in a typical bedroom. The spectral profiles of all signals were evaluated in five different bedrooms and the Victoria University sleep laboratory. No differences of importance were evident between spectral profiles of the different sounds in the different environments and at different volumes. All sounds except the 3100 Hz pure tone were created on a computer. The 3100 Hz signal was from a recording of a smoke alarm.[15] Note that the square waves have a fundamental frequency and then a series of subsequent peaks at the 3rd, 5th, 7th *etc* harmonics (i.e. multiples of the fundamental frequency).

Tactile signals: Two tactile devices were used. The pillow shaker was adapted from the "Visit" bed shaker from Bellman and Smyfon AB of Sweden (which is recommended to be placed under the pillow) and the bed shaker was adapted from the Vibralarm VSS12 device. Both tactile devices vibrated with both a vertical and horizontal displacement which was generated by an off-centre spinning weight inside each device. The bed shaker was placed under the mattress such that it would be as close as possible to being directly under the sleeper's navel. The pillow shaker was placed inside a small linen bag and attached to the underside of the centre of the sleeper's top pillow with a safety pin. This was to prevent it shaking itself loose from under the pillow. This was

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[14] This signal has been called the "mixed T-3" in earlier studies (Ball and Bruck, 2004, Bruck et al 2004, Bruck et al 2006, Bruck and Thomas, 2007)

[15] Thanks to Kidde for providing this sound file.

consistent with the recommended placement discussed within the local deaf community. The two tactile devices were adapted for this study such that each had five levels of intensity (achieved by controlling input voltage) under documented conditions. The intensity of each shaker when it came "off the shelf" was a little below level 3, and for other intensities 1 was the lowest level and 5 was the highest. Full procedural details of the intensity testing of the tactile devices are presented in Appendix A. The different intensities of the tactile device are given in Table 4.3(section 4.4 below). Pilot testing of tactile devices on the market showed that those with a pulse vibration alternated with a minimum of about one second on and one second off. Both tactile devices were modified to be in a T-3 pulsing pattern. It should be noted that both shakers made a slight noise, which was especially audible when the device was under the pillow. In the companion report on the alcohol impaired (Bruck, Thomas and Ball, 2007) a questionnaire was completed by each Sleep Technician documenting bed and pillow information. No differences were found in arousal threshold to the tactile devices as a function of any variations in bed and pillow type. Photos of the bed and pillow shaker can be found in Appendix G.

Strobe Light: The strobe lights[16] were presented to sleeping individuals at three levels of intensities, A, B and C. The different intensities of the strobe lights were achieved through presenting between one and three strobes simultaneously where level A involved one strobe being activated and level C involved three lights being on.   All three levels were above the 110 cd intensity level specified in the NFPA 72.[17] In addition, a single strobe (i.e. the weakest intensity tested, level A) was stronger than commercially available strobes. Full procedural details and results of the intensity testing of the strobe lights are presented in Appendix B. It was found that level A was 177 cd, level B was 210 cd and C was 420 cd. Strobes are required to pulse with a frequency between 1 and 2 Hz (NFPA 72) and the change for this study to be a modified T-3 pattern meant its frequency was three virtually instantaneous flashes over 1 second with a gap of 1.5 seconds between each set of three flashes. This makes it effectively a 2 Hz pulse within each set of three flashes (see Figure 4.1).

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[16] Purchased from Jaycar, Australia, 240V, 75 Watts.

[17] In this study the strobes were at below ceiling level and thus the 110 cd standard would apply. The 177 cd level is specified for a ceiling placement.
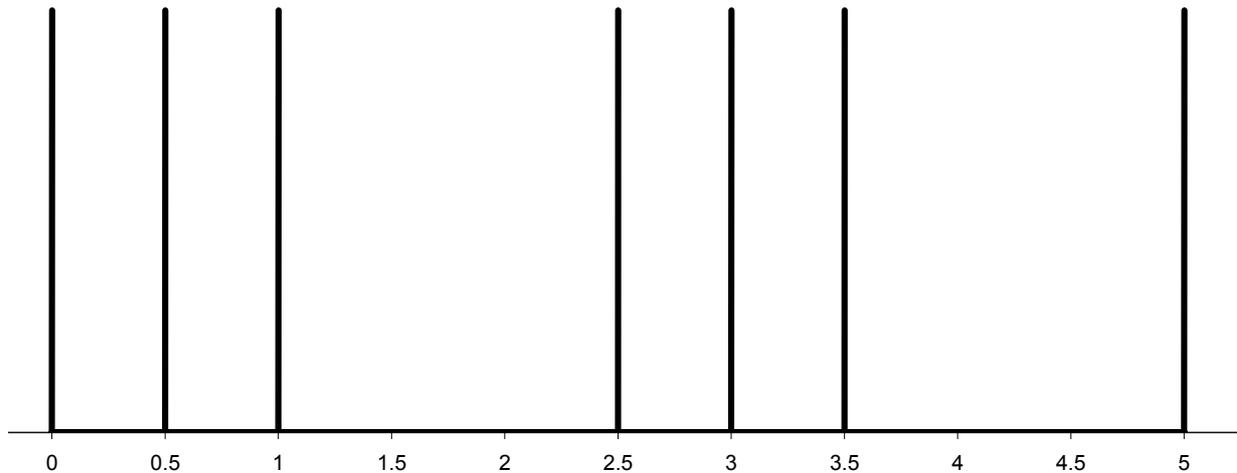
Figure 4.1: Flash pattern of the strobe lights as a function of time in seconds (cycle of three is repeatedly ongoing)

The strobe lights made a small clicking noise with each pulse. When one light was on the volume was 41 dBA, two lights 43 dBA and three lights 46 dBA. The strobe lights were mounted vertically on aluminium stands and positioned at the end of the bed (in line with the sleeping person), so as to be less affected by the sleeping position of the head. See Appendix H for instructions given to the Sleep Technicians for setting up the strobe light and Appendix G for a photo of the three strobes when set up.

Sleep recording and environment: Polysomnographic recordings were conducted using the Compumedics Siesta wireless data acquisition system or Compumedics Series E data acquisition system. The equipment transmitted EEG data, either via radio waves or a cable, to a laptop monitored by a Sleep Technician (ST) in another part of the house. Sounds were emitted from a speaker that was placed one metre from the centre of the participant's pillow, directly facing the pillow. The speaker was attached to the laptop via a ten metre extension cord. A button was placed beside the bed to receive the participant's behavioural response. This button illuminated a small blue light located near the ST when pressed by the participant. The behavioural response button and light were also connected via a ten metre extension cord. Further details pertaining to the auditory signal delivery equipment can be found in Appendix I.

Normally participants were tested in their own homes, in their bedroom with the door shut. The Sleep Technician monitored their sleep and presented the signals via a

laptop normally positioned in the hallway outside their bedroom. Participants had the option to sleep in the Victoria University Sleep Laboratory, which consists of two separate bedrooms and an experimental room. Three participants chose to undergo their testing in the Sleep Laboratory. For each person all nights of testing were conducted in the same environment and with the same ST. For the sleep recordings gold cup electrodes with Grass Electrode Cream were used for the scalp electrodes (C3 and C4), and mini-dot snap-on electrodes were used for all others.

Prior Sleep and Alcohol Consumption Questionnaire: To check that participants did not have a significantly worse than usual night's sleep the night before testing, and to enquire about prior alcohol consumption, all participants completed the questionaire asking for a self report on such issues (see Appendix J).

Alerting Devices Questionnaire: A four page questionnaire asked a range of questions on demographic issues, history of hearing loss, how confident the participant was about hearing different signals during the day and night (e.g. doorbell, phone, fire alarm), any alternative alerting devices they may have and whether they considered it important for them tho have such devices (and if not, why not). The questionnaire is contained in Appendix K.

4.3 Procedure

After each volunteer had given informed consent a Project Officer visited the volunteer's home in order to complete the hearing screening test, AWAKE testing and Alerting Devices Questionnaire on a day prior to the sleep testing. For those who met the hearing criteria the AWAKE testing sounds were tested in the quietest room of the house (and preferably the bedroom). A chair was arranged so that the participant was seated FACING the speakers at a distance of about 1 meter, such that the sounds reached both ears equally. After the sound volume was calibrated (see Appendix I) the participant was given the behavioural response button and told to press it when they could hear the sound. Each sound was presented for 30 seconds at a time with a 5 second silence in between. The commencing volume was at a lower level that the hearing screening test suggested they could hear. Each sound was presented such that the same threshold level was obtained for each sound across two separate

presentations at the same decibel level. Increments were at 5 dBA. The test administrator was seated such that they were not in the direct line of vision of the participant.

Those who met the eligibility criteria from the hearing test were then administered the Alerting Devices Questionnaire. They were then assigned to a Sleep Technician (ST) who contacted them to arrange a mutually convenient time for the ASLEEP phase to take place. During this contact the importance of avoiding alcohol on the day of testing and ensuring sufficient prior sleep were emphasised.

Data was collected by a team of paid STs. For ethical reasons the sex of the ST matched that of the participant. Six signals were tested across two nights (three signals per night as far as possible). Signals were presented in a counterbalanced order and testing nights were usually one week apart, but always with a minimum of three intervening nights to allow for adequate sleep recovery. The ST arrived at the participant's home approximately one and a half hours prior to the participant's usual bedtime. The electronic equipment was set up including the laptop, speakers, pillow and bed shakers, strobe lights, and behavioural response light. All equipment was set up on both occasions, regardless of whether they were to be used on any given night. This allowed the minimisation of priming effects by telling the participant each night that they would be awoken to something they may see, hear or feel. Background sound levels were measured and recorded, and sound levels were calibrated at the pillow. Full details of this are contained in Appendix I.

After the equipment was correctly set up, the electrodes for polysomnographic recording were applied. Electrodes were attached according to the standard placement set down by Rechtschaffen and Kales (1968). Electroencephalogram (EEG) electrodes were attached at C3, C4, A1 and A2. Electro-oculogram (EOG) electrodes were placed at approximately 1cm above the outer canthus of the eye on one side, and at approximately 1cm below the outer canthus of the other eye, and electromyogram (EMG) electrodes were placed beneath the chin. Additionally, a reference electrode was affixed to the middle of the forehead, and a ground electrode was placed at the collarbone. Before electrodes were attached, the skin was cleaned firstly with an alcohol swab, and then with Nuprep abrasive cream.

After the electrodes had been applied and tested participants were settled in bed and instructed on the procedure to follow when they became aware of the signals sounding. They were asked to depress the behavioural response button placed next to their bed three times to signify that they were awake immediately upon becoming aware of a signal. They were reminded that the signal may be something they could see, hear, or feel. Lights were then extinguished.

After lights out the ST monitored the participant's EEG output until slow wave sleep (SWS, stage 3 and/or 4) sleep was confirmed for a minimum of three consecutive 30 second epochs. Once SWS was confirmed the signal delivery system was activated to start the required stimulus at the lowest experimental level. When a participant responded by pressing the behavioural response button, the ST alerted the signal delivery program to record the exact time, and the stimulus was terminated. Details of stage of sleep when different signals were presented are given in Section 5.9 and Appendix L.

All polysomnographic data were saved and perused at a later date to determine the exact point of awakening. It is theoretically possible to determine the exact moment of alertness by noting changes in the EEG and EMG. For each awakening the polysomnographic data were examined and the time at which the EEG waves altered from the patterns characteristic of sleep (in its various forms) to a wake pattern (very low amplitude and high frequency waves) was recorded. This was usually (but not always) accompanied by an increase in muscle tone. The exact determination of the time of EEG wakefulness was not always clear and where there was ambiguity, the time at which changes occurred in both tracings was selected.

For all signals presented during sleep the methodology followed a procedure called "the method of discrete limits". Each signal was presented in discrete episodes of 30 seconds. If the participant continued to sleep (assessed behaviourally by a failure to press the bedside button) a pause occurred (for most signals this pause was for 30 seconds). Once this had passed, if the participant remained asleep, the signal was presented again at an increased intensity. This procedure continued until the participant pressed the button. If they did not wake to the highest signal intensity then,

after the normal pause, the highest signal intensity was played for a further three minutes. Thus they would receive the maximum intensity of the signal for a total of three and a half minutes. All signals at each intensity level commenced from a nil intensity, simulating the sudden onset of an emergency signal. Table 4.2 sets out the relevant temporal specifications of the delivery of the different signals and Table 4.3 gives the intensity measurements at each level for the auditory and tactile signals. Notice that the auditory and tactile signals had five levels, while the strobe only had three.

To ensure that all signals were presented across the identical time frame (eight minutes) the pauses between the levels of strobe intensity were lengthened from 30 seconds to 70 seconds. This was considered especially important as all signals were to commence during SWS but continued to be presented even if the sleep stage changed. Having one signal being presented at increasing intensities across a different time period would introduce a possible confound and this needed to be avoided.

Table 4.2: Temporal specifications of signal delivery

	Number of levels	Signal _on_ duration	Signal _off_ duration	Total time
Auditory signals	5	30 sec	30 sec	8 min
Bed shaker	5	30 sec	30 sec	8 min
Pillow shaker	5	30 sec	30 sec	8 min
Strobe lights	3	30 sec	70 sec	8 min

This research was approved by the Victoria University Human Experimentation Ethics Committee.

4.4 Data analysis

In the AWAKE phase the dependent variables were the lowest decibel level at which the participant noted on two occasions that they could hear each of the eight signals. Descriptive statistics and a repeated measures ANOVA, with paired comparisons, were conducted to determine which sounds had the lowest response thresholds under the testing conditions.

There were two measures of awakening recorded in the ASLEEP phase;

1. *EEG wake time*, which was the exact time (in seconds) of awakening as determined by the scoring of the sleep recording. This was recorded as the total time from the commencement of the lowest level signal presentation to EEG defined wakefulness.

2. *Behavioural response time*, which was the total time (in seconds) from the commencement of the lowest level of signal presentation to the time the subject began to press the behavioural response button by their bedside to indicate that they had woken up.

Where the subject slept through, a time of 500 seconds was assigned for both 1 and 2 above. This was 20 seconds longer than the actual total time from signals commencement to termination.

From the EEG wake time data an ordinal variable, termed the *Waking Score*, was calculated according to the details set out in Table 4.3. This table shows that the score achieved relates to the time point at which the person awoke, which directly relates to the intensity level of the signal to which a person awoke, either to the onset of the signal (odd Waking Scores), or its offset (even Waking Scores). If the person did not wake at all a score of 12 was assigned. Thus, for example, if a person first showed EEG wakefulness during the silence that followed the presentation of one of the auditory signals at 85 dB they would receive a score of 8 for this dependent variable. For auditory signals the requirement that a sound be received at the pillow at 75 dBA was referred to as the "benchmark". This is consistent with the minimum volume often recommended at the pillow for smoke alarms (see Section 2.3). For the bed and pillow shakers the intensity level of the shakers when they were purchased was called the "benchmark" and this corresponds to just a little below level 3 (exact comparisons are in Appendix A). While subjectively there was a substantial difference between the pillow

shaker and bed shaker, the numerical differences shown in Table 4.3 were greater than expected. It seems possible that human respond to the different levels of vibrations on a logarithmic scale. For the strobes all three levels, A, B and C were above the standard (NFPA 72, 2002). For illustrative purposes in the Results strobe intensities A to C were deemed to be equivalent to Waking Scores of 5-12.

The dependent variable of behavioural response time is more sensitive to minor variations in responsiveness than the Waking Score and is thus also worth examining statistically.

The design of the study was repeated measures, wherein as far as possible all participants received six different signals, thereby minimizing the uncontrolled influence of individual differences. To allow such analyses across the complete data set, where not each participant received each of the possible signals (see Section 4.1), independent groups analyses were used.

The Waking Scores, behavioural response time data and the EEG wake time data were not normally distributed so inferential statistics (e.g. t-tests, ANOVAs) were not the statistic of choice for these dependent variables. In these cases the data was sometimes bimodal, being grouped at the lower points and uppermost level. Thus descriptive statistics, frequency analyses, percentages and non-parametric statistics (the Mann Whitney U Test for two group comparisons and Kruskal-Wallis Test for three or more variables) were used with such variables. Where the data was normally distributed (e.g. for the AWAKE testing) inferential statistics were used.

All data was analysed using the Statistical Package for the Social Sciences (SPSS, version 14) and the required level of alpha for significance was set at $p < .05$.

Table 4.3: Temporal and intensity details of auditory and tactile signal presentations and corresponding Waking Score (based on EEG waking time).

TIME → → → → → → → →											
Waking Score	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12** Did not wake
Signal intensity	Level 1 (30 sec)	No signal (30 sec)	Level 2 (30 sec)	No signal (30 sec)	Level 3 (30 sec) BENCHMARK	No signal (30 sec)	Level 4 (30 sec)	No signal (30 sec)	Level 5 (30 sec)	No signal (30 sec)	Level 5 (3 min)	
Auditory signals	55 dBA	No signal	65 dBA	No signal	75 dBA	No signal	85 dBA	No signal	95 dBA	No signal	95 dBA	
Bed shaker	1.09 ms^{-2}	No signal	1.56 ms^{-2}	No signal	1.91 ms^{-2}	No signal	2.10 ms^{-2}	No signal	2.41 ms^{-2}	No signal	2.41 ms^{-2}	
Pillow shaker	.086 ms^{-2}	No signal	.187 ms^{-2}	No signal	.258 ms^{-2}	No signal	.294 ms^{-2}	No signal	.533 ms^{-2}	No signal	.533 ms^{-2}	

5 Results

Phase 1: AWAKE testing

5.1 Hearing thresholds to auditory signals

Comparisons were made of the AWAKE hearing thresholds across all eight signals presented, using a repeated measures ANOVA. The result approached significance but did not reach the alpha level criterion of 0.05 ($F_{(7,31)}=2.25$, $p=.056$). The descriptive statistics are shown in Table 5.1. These showed that the 520 Hz square wave signal had the lowest mean response threshold, while the 3100 Hz pure tone had the highest response threshold. On the basis of this data the two signals with the lowest response thresholds, 520 Hz square wave and 400 Hz square wave, were selected to be used in the ASLEEP phase (i.e. as X and Y). It should be noted that in several cases the threshold differences between signals were very small. The paired comparisons between the different signals are displayed in Table 5.2 are show that both the white noise signal and the 3100 Hz pure tone were very significantly different than the two square wave signals.

Table 5.1: Descriptive statistics of the auditory response thresholds (dBA) for signals presented in the AWAKE phase.

Auditory signals – AWAKE phase	Mean (Standard deviation)	Median	Range
400 Hz square wave	51.71 (8.6)	50	40-75
520 Hz square wave	50.39 (8.5)	50	35-65
White noise	56.18 (10.8)	55	40-75
400 - 1600 Hz rising whoop	52.76 (11.8)	55	35-80
400 – 800 Hz rising whoop	53.42 (13.6)	52.5	35-80
3 pure tones; 400, 800 1600 Hz	51.84 (11.5)	52.5	35-80
500 Hz pure tone	51.84 (11.5)	52.5	35-75
3100 Hz pure tone	57.90 (15.2)	57.5	35-95

Table 5.2: Matrix showing the level of significance for pair-wise comparisons across the eight signals (using Least Significant Difference statistic) in the AWAKE phase.

blank = not significant, *p<.05, **p≤.01.

	400 Hz square wave	520 Hz square wave	White noise	400 - 1600 Hz whoop	400 – 800 Hz whoop	3 pure tones; 400, 800 1600 Hz	500 Hz pure tone	3100 Hz pure tone
400 Hz square wave								
520 Hz square wave								
White noise	**	**						
400 - 1600 Hz whoop								
400 – 800 Hz whoop								
3 pure tones; 400, 800 1600 Hz			*					
500 Hz pure tone			*					
3100 Hz pure tone	**	**		*		*	*	

Phase 2: ASLEEP Testing

5.2 Waking Scores

Waking Scores were calculated for each participant for the tactile and auditory signals and examined in relation to whether the score indicated they

- awoke at or below the benchmark for that signal (i.e. Waking Score ≤ 5),
- awoke above the benchmark (i.e. Waking Score >5 and <12), or
- slept through (i.e. Waking Score = 12).

All presented strobe intensities (i.e. A, B and C) were above the benchmark (or standard). (The Waking Score and benchmarks are described in Section 4.4 and Table 4.3 above.)

Table 5.3 shows the number and percentage of participants who fell into each category for each different signal. Considering first the percentage who slept through all presentations

of the signals (including the 3.5 minutes at the highest intensity) it can be seen that the strobe lights, the 3100 Hz pure wave and the bed shaker had the highest proportion of people who slept through. In contrast, no participants slept through the 520 Hz square wave auditory signal. Given that all strobe levels were above the standard, they clearly performed the worst of all signals presented.

Table 5.3: Number and percentage of participants in terms of their waking behaviour to different signals.

	Awoke at or below benchmark		Awoke above benchmark		Slept through all levels	
	Number	%	Number	%	Number	%
400 Hz square wave	32/37	86.5%	3/37	8.1%	2/37	5.4%
520 Hz square wave	33/36	91.7%	3/36	8.3%	0/36	0.0%
3100 Hz pure tone	18/32	56.3%	9/32	28.1%	5/32	15.6%
Bed shaker	28/35	80.0%	3/35	8.6%	4/35	11.4%
Pillow shaker	25/30	83.4%	4/30	13.3%	1/30	3.3%
	Awoke at level A		*Awoke at level B or C*		*Slept through*	
Strobe light*	10/37	27.0%	11/37	29.8 %	16/37	43.2%

*For the strobe light all levels were above the benchmark

The mean, standard deviation, median, and range for Waking Scores for all signals are shown in Table 5.4. Consistent with the data in Table 5.3, the mean and median scores in Table 5.4 clearly indicate that the 3100 Hz pure wave and the strobe light resulted in the poorest waking response.

Table 5.4: Descriptive statistics for the Waking Scores for all signals.

	Mean Waking Score (standard deviation)	Median (and dBA level for sounds)		Range
400 Hz square wave	2.91 (3.0)	1	(55 dBA)	1-12
520 Hz square wave	2.61 (2.5)	1	(55 dBA)	1-11
3100 Hz pure tone	5.43 (4.0)	5	(75 dBA)	1-12
Bed shaker	3.43 (3.9)	1		1-12
Pillow shaker	2.97 (3.6)	1		1-12
Strobe light*	9.16 (3.0)	9		5-12

*For the strobe light the Waking Score varied from 5 to 12 as all levels were above the benchmark

In order to test for statistical differences between the three auditory sounds a Kruskal-Wallis test was performed using the Waking Score as the dependent variable and a highly significant difference was found (x^2=12.47, df=2, p=. 002). The pattern of results suggests that the two square wave sounds were significantly more effective at waking people who are hard of hearing than the 3100 Hz signal. To test for differences between the two tactile signals a Mann Whitney U- test was performed using the Waking Score and no significant difference between the bed and pillow shaker was found (U=456, p=.30).

Figure 5.1 presents the Waking Score cumulative frequencies for the auditory signals and Figure 5.2 for the tactile signals and strobe lights.   Waking Scores from 1 to 11 are shown. Figure 5.1 shows that the cumulative percentage of participants who awoke to the 3100 Hz signal was less for each Waking Score compared to the other auditory signals, indicating less efficacy. A similar pattern can be seen in Figure 5.2, where at Waking Score 11 less than 60% had awoken to the strobe, while over 80% had awoken to the tactile devices.
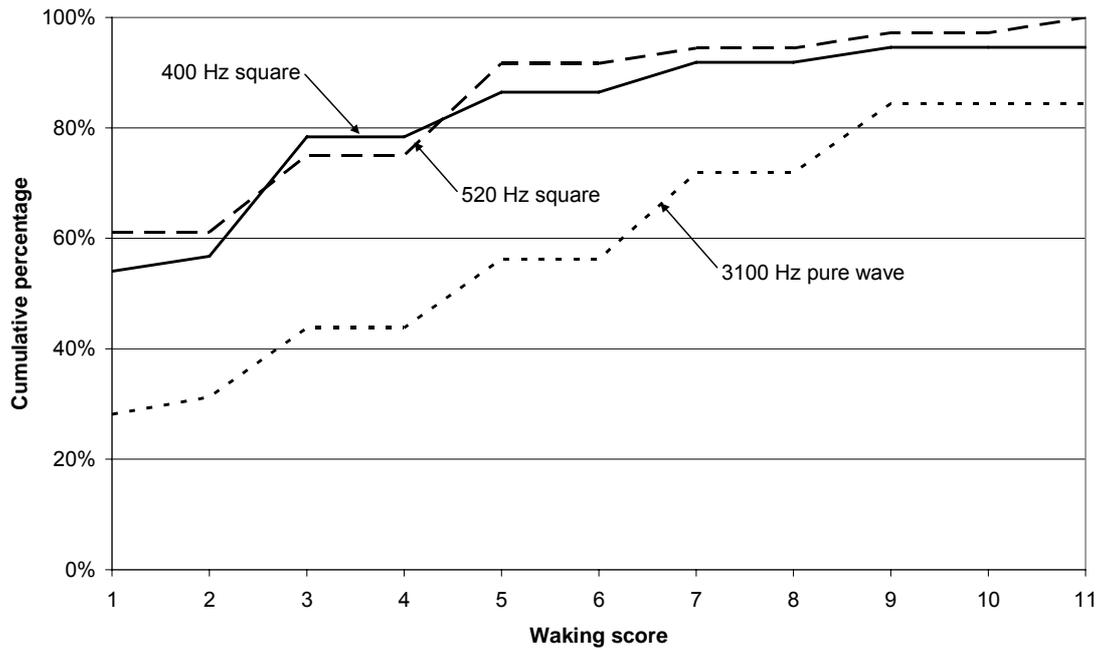
Figure 5.1: Cumulative frequency graphs for Waking Scores for the three auditory sounds.
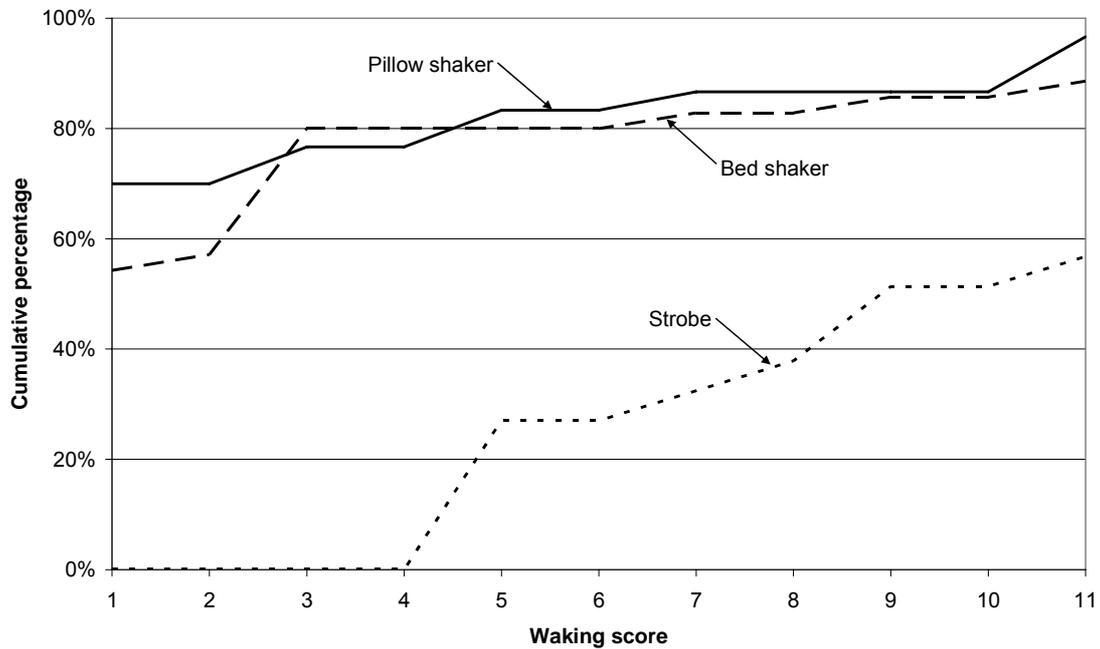
Figure 5.2: Cumulative frequency graphs for Waking Scores for the two tactile signals and strobe lights. (Note that for the strobe lights Waking Scores commenced from level 5.)

5.3 Comparison of AWAKE and ASLEEP thresholds

In order to determine the relationship between a person's auditory threshold to a sound when awake and their waking threshold when asleep a series of Pearson's correlations were performed. The following results were found when the AWAKE threshold (dBA) was correlated with the Waking Score achieved in the ASLEEP phase

- 400 Hz square wave, r=.34, p=.035, 12% of variance explained by the relationship
- 520 Hz square wave, r=.39, p=.018, 15% of variance explained by the relationship
- 3100 Hz square wave, r=.49, p=.005, 24% of variance explained by the relationship.

These results show that the strongest relationship was found for the high frequency sound. However, even though this relationship was very significant statistically there is a large amount of the variance in the data that is not explained by the relationship. Thus the utility of using the AWAKE threshold to predict the ASLEEP threshold would not be high.

A comparison of the median response threshold when AWAKE to the median response threshold when ASLEEP for the three different auditory signal showed that for the 400Hz and 520 Hz square waves the difference was 5 dBA, while for the 3100 Hz pure wave it was 17.5 dBA (values can be found in Tables 5.1 and 5.4).

A further analysis was completed to determine the whether the high frequency hearing screening data (4000 Hz for left and right ears) or the AWAKE testing of the 3100 Hz signal could be used to predict the 14 participants who slept through the benchmark for the 3100 Hz signal (i.e. 75 dBA). The relevant descriptive data are shown in Table 5.5. The table shows that there was a large standard deviation and large range for all the wake hearing threshold data, indicating that these variables cannot be used to predict who may sleep through the current high pitched smoke alarm.

Table 5.5:   Hearing threshold data in decibels (when awake) for the participants who slept through the benchmark for the 3100 Hz signal (n=14).

	Mean (SD)	Range
L4000 screening	55.4 (15.7)	25-90
R4000 screening	57.3 (11.1)	40-75
3100 Hz AWAKE testing	64.6 (16.9)	35-95

5.4 Signal Onset and Offset

The timing of awakenings in relation to signal onset and offset were analysed such that calculations were made of how many participants

- awoke soon after signal onset (within 10 seconds),

- during the rest of the ongoing signal (i.e. normally 11-30 seconds after signal onset),

- within 10 seconds of signal offset, and

- during the remainder of the no signal pause (with this being a further 20 seconds for all signals except the strobe where the pause was for a further 60 seconds).

Figure 5.3 presents the percentage with which each type of awakening occurred and shows that for the auditory and tactile signals most awakenings were within 10 seconds of signal onset. The pattern of these results suggests that the T-3 signal (with its intermittent 1.5 second gap) is perceived as a continuous signal when asleep, as the onset produced more awakenings than during the signal playing continuously. The graph also shows that very few awakenings (five) occurred during signal offset.   In considering Figure 5.3 it must be remembered that the percent awakening within each category (e.g. within 10 seconds of signal onset) applies to each signal at the level at which awakening took place (if it did).
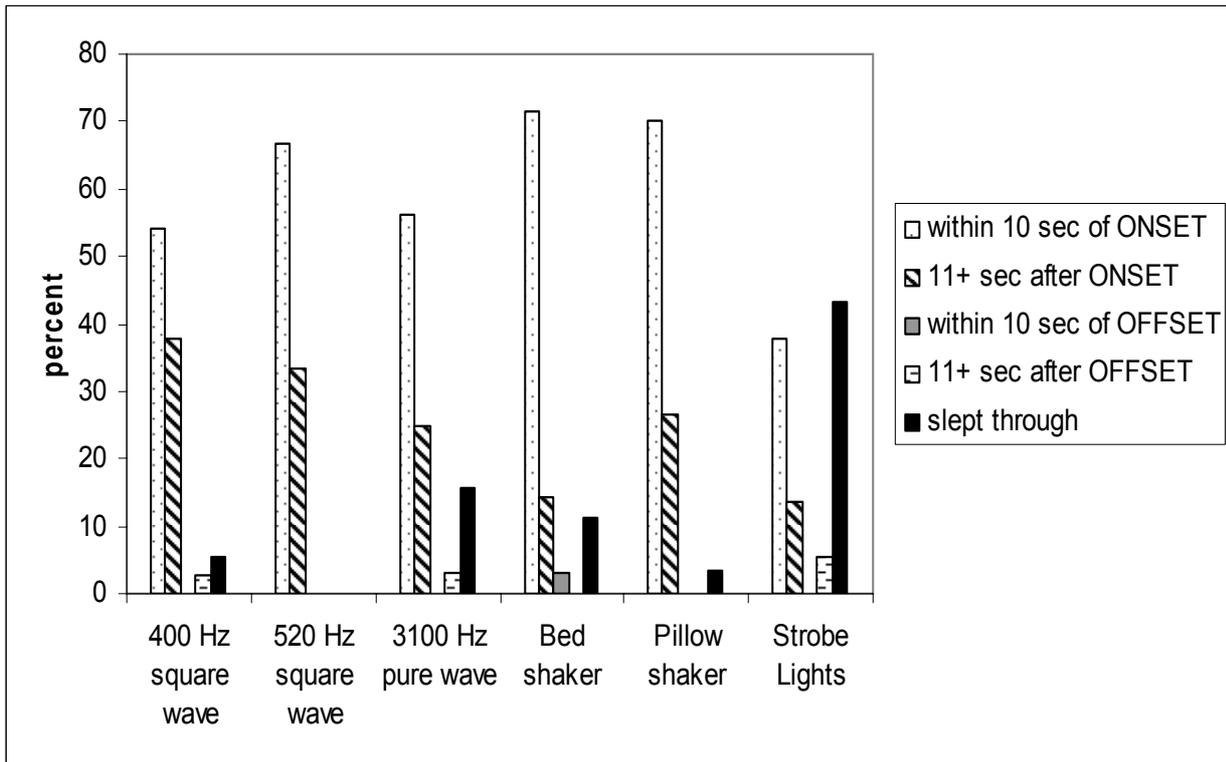
Figure 5.3: Percentage of awakenings as a function of timing of the onset and offset of each signal.

5.5 Sex differences

The possibility of sex differences in the waking effectiveness of different signals for hard of hearing people was statistically investigated. For this analysis Mann Whitney U tests were performed for each signal with the Waking Score as the dependent variable and sex as the independent variable. Results are displayed in Table 5.6. No significant sex differences or trends were found for any of the signals.

5.6 Age differences

The sample was split between those aged under 60 years and those aged 60 or over. The Waking Scores of the two groups were compared for all signals as a function of age and the results are shown in Table 5.7. It can be seen that the only signal that differed significantly between the two age groups was the bed shaker. The results suggest the bed shaker is significantly less effective for those aged over 60 years than for the younger age group.

Table 5.6: Descriptive and non-parametric statistics for the Waking Scores for all signals as a function of sex.

	Mean Waking Score (standard deviation)		Mann Whitney U results	
	Males	Females	U statistic	p level
400 Hz square wave	2.53 (2.4)	3.18 (3.4)	155.5	.75
520 Hz square wave	3.40 (2.9)	2.04 (2.1))	112.5	.10
3100 Hz pure tone	5.25 (4.1)	5.55 (4.0)	112.0	.75
Bed shaker	3.93 (4.0)	3.05 (3.8)	126.0	.38
Pillow shaker	3.17 (4.1)	2.83 (3.4)	103.0	.80
Strobe light*	8.73 (3.3)	9.45 (2.79)	144.5	.50

*For the strobe light the Waking Score varied from 5 to 12 as all levels were above the benchmark

Table 5.7: Descriptive and non-parametric statistics for the Waking Score for all signals as a function of age.

Signal	under 60 years		60+ years		Mann Whitney U results	
	N	mean (SD)	N	mean (SD)	U statistic	p level
400 Hz square wave	20	2.9 (2.5)	17	2.9 (3.6)	152.5	.56
520 Hz square wave	20	3.0 (2.7)	16	2.1 (2.3)	123.0	.18
3100 Hz pure tone	19	6.1(3.7)	13	4.5 (4.0)	97.5	.31
Bed Shaker	19	2.3 (2.8)	16	4.8 (4.6)	96.0	.04
Pillow Shaker	16	2.6 (3.6)	14	3.4 (3.8)	89.0	.24
Strobe*	19	9.3 (3.3)	18	9.0 (2.8)	97.5	.31

*For the strobe light the Waking Score varied from 5 to 12 as all levels were above the benchmark

The failure to find any age group related difference in Waking Scores for the 3100 Hz signal prompted a post-hoc analysis of the hearing screening thresholds as presented in Appendix D.2. A criterion for suspected presbycusis was arbitrarily established as requiring a 4000 Hz hearing threshold greater than or equal to 55 dBA[18] in both ears and being aged over 60 years. It was found that only four participants had suspected presbycusis using this criterion. Given this small number it was not surprising that there was no age group difference in arousal thresholds for the 3100 Hz signal.

5.7 Behavioural Response Time

Table 5.8 summarises the descriptive statistics of the behavioural response time (in seconds) for each signal. Where a participant slept through a signal a behavioural response time of 500 seconds was arbitrarily assigned. For this reason it may be most instructive to consider the median behavioural response times. The Kruskal-Wallis test comparing the three auditory sounds found a highly significant difference (x^2=12.97, df=2, p=.002), and inspection of the data shows that this was due to the particularly poor performance of the 3100 Hz pure wave. A Mann Whitney U test found no significant difference between the two tactile signals (U=467, p=.45).

Table 5.8: Descriptive statistics for behavioural response time (in seconds) across the different signals. (Note that all times include silences.)

	Mean (standard deviation)	Median	Range
400 Hz square wave	84.1 (118.9)	29.0	6-500
520 Hz square wave	63.4 (77.8)	23.0	5-340
3100 Hz pure tone	180.7 (174.2)	131.0	9-500
Bed shaker	114.4 (167.7)	26.0	4-500
Pillow shaker	90.6 (143.3)	18.0	5-500
Strobe light*	286.4 (210.8)	233.0	5-500

* It must be remembered that for the strobe light the pause between signals was 70 seconds (not 30 sec as for other signals) and only three levels was presented (not five as for the other signals).

[18] Selected as 55 dBA was the lowest volume presented in this study and also informed by the mean hearing threshold for 60-69 year old males at 4000 Hz (Cruickshanks et al. 1998).

The differences between the EEG wake time and the behavioural response time was calculated for each signal as this is indicative of the time required between the brain becoming awake and responding behaviourally as instructed (pressing a bedside button three times). This may be indicative of sleep inertia. Cases where the participant slept through were excluded from this analysis. The descriptive data for this time difference is summarised in Table 5.9 as a function of the different signals.

Table 5.9: Descriptive statistics for the mean differences between behavioural response and EEG awake times

	Mean (standard deviation)	Range	Median
400 Hz square wave	8.3 (8.5)	1-39	5
520 Hz square wave	6.7 (5.1)	1-28	6.5
3100 Hz pure tone	13.5 (44.9)	1-254	5.0
Bed Shaker	13.1 (31.3)	1-186	7
Pillow Shaker	11.4 (15.4)	2-71	6
Strobe	6.9 (7.8)	1-76	1

A one way ANOVA was performed across all six signals for the time difference between EEG wakefulness and behavioural response time (mean values as in Table 5.9) and no significant difference was found between the signals (F=0.58, df = 5, p=.72). Inspection of the ranges shows a large variability in times taken to respond behaviourally once awake. Perusal of the raw data found no evidence that the longer response times were consistently produced by the same small group of individuals.

5.8 Signal combinations

One question of interest is whether two different signals (e.g. auditory and tactile) would provide a substantial advantage over one signal alone. One way to consider this is to examine whether a person who has difficulty waking to one type of sensory signal would be more likely to wake to a different sensory signal. This was explored by splitting the group into lighter and deeper sleepers. Because the 520Hz square wave was the single

best performing signal, and thus may be part of any kit of multiple signals, it was used to split the group. As the behavioural response data was the dependent variable with the greatest spread of variability, the 520 Hz square wave median value for this variable (23.0 seconds) was used to split the sample (i.e. "lighter" sleepers had a 520Hz square wave behavioural response time of less than the median). Mann Whitney U tests using the Waking Scores were performed to determine possible group differences.

Table 5.10: Descriptive and non-parametric statistics for Waking Scores when the sample was split into lighter and deeper sleepers according to responsiveness on the 520 Hz square wave (see text).

Signal	N		mean (SD)		Mann Whitney U	P level
	lighter sleepers	deeper sleepers	lighter sleepers	deeper sleepers		
400 Hz square wave	18	19	1.5 (1.2)	4.2 (3.6)	83.5	.007
520 Hz square wave	18	18	1.0 (0.0)	4.2 (2.8)	36	.000
3100 Hz pure tone	16	16	3.4 (3.3)	7.5 (3.6)	48.5	.002
Bed Shaker	17	18	3.4 (4.2)	3.4 (3.7)	145.5	.79
Pillow Shaker	15	15	2.1 (2.9)	3.8 (4.1)	89	.23
Strobe	16	16	8.5 (3.2)	9.8 (2.7)	136.5	.27

Table 5.10 shows that being a lighter or deeper sleeper on the 520 Hz square wave was associated with a similar classification on the other two auditory signals. However, the non-significant differences shown for the tactile and strobe signals suggest that different people respond differently to different sensory devices. Thus while all the auditory signals tended to split the group between lighter and deeper sleepers in a similar way, the other devices split the sample differently. This data provides tentative support for the advantage of combining two different types of sensory signals (e.g. a 520 Hz square wave and a tactile signal) for waking people up.

5.9 Sleep stage data:

Overall, 93.4% of signal presentations occurred during slow wave sleep (SWS, stages 3 and 4). As people aged over 60 years have less slow wave sleep than younger adults

(Ohayon et al. 2004), Sleep Technicians were advised to aim for stage 3 sleep if it became clear that participants aged 60 years and older had reduced pressure for stage 4 sleep early in the night and were thus unlikely to have sufficient stage 4 sleep to cover all three awakenings on any given night. If this occurred, they were instructed to conduct all signal presentations for that person in stage 3. In aiming for stage 3 some errors occurred, resulting in a higher level of stage 2 awakenings for the group aged 60 and above. Specifically it was found that 98.9% of awakenings were from SWS for those aged under 60 years and 87.8% for those 60 years or over. Careful examination of the data suggested there were no problematic data implications in whether participants had certain signals presented in SWS or stage 2 sleep. See Appendix L for the descriptive statistics and analyses on this issue.

5.10 Alerting Devices Questionnaire

This questionnaire was administered to all volunteers who met the selection criteria for Phase 1 and 2 of the study. The overall number of participants was 44, indicating that six of these participants chose not to proceed to the ASLEEP phase of the study. As shown in Table 5.11 the sample was spread across all adult age groups, with slightly more females represented than males. Two thirds of the sample estimated that their hearing loss began prior to the age of 45 years. Around two thirds of the sample wore hearing aids at least sometimes, although very rarely when sleeping. The questionnaire data revealed that 98% did not have either a non-auditory alarm or a specialised low frequency audible alarm[19] and 84% did not feel the need for an alternative smoke alarm. Figure 5.4 shows the reasons reported as to why the respondents did not have an alternative emergency alarm. Among the respondents a substantial percentage (39%) were not confident the sound of a smoke alarm would wake them and could not rely on someone else in the house.

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[19] One respondent had a sprinkler system.

Table 5.11: Demographics and selected responses (n=44)

		Percentage
Age group	18-44 yrs	30
	45-64 yrs	26
	65+ yrs	44
Sex	Male	41
	Female	59
Estimated age of hearing loss onset	0-17 yrs	28
	18-44 yrs	37
	45-64 yrs	21
	65+ yrs	14
Wear hearing aids outside home	Not applicable/Never	34
	Sometimes	23
	Always	43
Wear hearing aids at home	Not applicable/Never	37
	Sometimes	35
	Always	28
Wear hearing aids when sleeping	Not applicable/Never	95.5
	Sometimes	4.5
	Always	0.0
Live alone	No	74.5
	Yes	25.5
Have an alternative device for a fire emergency	No	98
	Yes	2
Feel need for an alternative fire alarm	No	84
	Yes	16
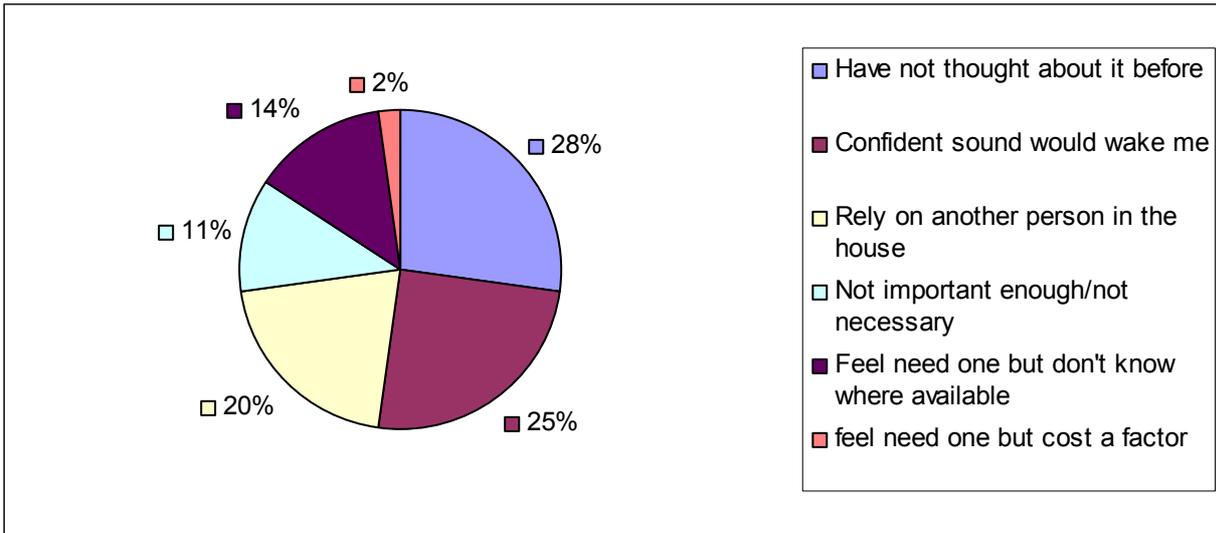
Figure 5.4: Pie chart of reasons reported by hard of hearing participants who did not have an alternative alarm (n=43)

Table 5.12 sets out the responses to questions about the confidence which people felt about being able to hear certain sounds during the day and at night in bed. It can be seen that, of the people who relied on their hearing to alert them to a fire emergency during the day, 28% were not very confident they would be able to hear the fire alarm (responded as "somewhat" or "not at all" confident). When the question referred to waking to the fire alarm at night in bed this increased to 43.2% being not very confident that the signal would awaken them. Almost all the people who responded "Don't rely on my hearing" relied on another person in the house.

Table 5.12: Responses to questions (percentages) on confidence will hear certain signals during the day or at night in bed (n=44 for most questions)

	Very confident	Somewhat confident	Not at all confident	Don't rely on my hearing
Confidence can hear front door during the day	41.9	25.6	7	25.6
Confidence can hear the telephone during the day	52.4	21.4	4.8	21.4
Confidence can hear a fire alarm during the day	55.8	23.3	4.7	16.3
Confidence will wake to sound of alarm clock at night	47.5	15	2.5	35
Confidence will wake to sound of front door at night	22.5	35	15	27.5
Confidence will wake to sound of telephone at night	47.6	19	9.5	23.8
Confidence will wake to sound of fire alarm at night	35.1	27	16.2	21.6

6   Discussion

6.1 Responsiveness to different signals

Auditory signals:

The AWAKE testing revealed that the two low frequency square waves (400 Hz and 520 Hz) had the lowest average response thresholds in this hard of hearing population. Statistically the differences were significant for these two square waves in comparison to white noise and the 3100 Hz pure tone (as in current smoke alarms). The mean and median values indicated the better performance of the square waves compared to other signals, although in several cases the differences were very small. Perhaps the inclusion of the harmonics (3rd, 5th etc) in the square wave of a low frequency tone is important in helping people hear the sound.

In comparing the waking effectiveness of the three auditory signals presented in the ASLEEP phase it can be seen that the two low frequency square waves (with 400 Hz and 520 Hz fundamental frequencies) again performed significantly better than the high frequency (3100 Hz) pure tone. The findings were quite clear and consistent across the different variables examined and the different analyses undertaken.

These analyses showed that:

- With the two square waves 87-92% awoke at or below the 75 dBA benchmark compared to 46% with the 3100 Hz signal.
- No participants slept through the 520 Hz square wave signal at 95 dBA, while 16% slept through the 95dBA 3100 Hz pure tone.
- A significant difference was found across the three auditory signals when the ordinal variable, Waking Score, was used. The mean and median values clearly show that the 3100 Hz tone was the least effective waking signal.
- Under the testing conditions the median Waking Score for the two square waves equated to a sound level of 55 dBA and the 3100 Hz tone, 75 dBA.
- The cumulative frequency graphs show clear visual evidence of the poorer waking effectiveness of the 3100 Hz tone.

- Behavioural response time (i.e. time from signal onset at the lowest intensity to pressing the bedside button) was significantly faster with the two square waves than with the 3100 Hz signal, with the median values showing differences of 100 seconds or more.[20]

The finding that a low frequency signal was more effective at waking hard of hearing participants than a high pitched signal is consistent with the findings of Du Bois et al. 2005. They showed that a 450 Hz signal of less than 75 dB aroused more adults who were hard of hearing than a 3000 Hz alarm signal. The effective performance of the low frequency square waves in the current study is also consistent with published findings in other population groups (children, sober and alcohol impaired young adults and older adults) reviewed in Section 2.3, where the signal was typically called the mixed T-3. [21]

It was found that hearing threshold when awake for a particular signal could not be used to accurately predict arousal threshold when asleep for the same signal. Nevertheless it was interesting that comparisons of the median response thresholds when awake and asleep for the same sounds showed that a much larger increase (17.5 dBA) was needed for the 3100 Hz pure tone when asleep compared to the two low frequency square waves (5 dBA). Analyses based on those participants who slept through the high pitched signal at benchmark levels provided no support for the idea that wake hearing thresholds can help predict who may sleep through a high pitched signal.

One question that arises is whether the single best square wave is actually one with a fundamental frequency of 520 Hz or whether one that has a higher fundamental frequency may be as effective or better. This question has importance given that it is technically more difficult to produce a high volume lower frequency sound than a sound with a higher frequency at the same decibel level. The key issues appear to be the power and speaker requirements, especially in single station, battery powered only smoke alarms. Our research team is about to commence comparative testing of the efficacy of the 520 Hz square wave compared to square waves with a fundamental frequency between 600 and 2000 Hz in sleeping unimpaired young adults. However, for hard of hearing people a fundamental frequency of 520 Hz or thereabouts seems likely to be the most effective.

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[20] This time, of course, includes the duration of the silences between signals.

[21] It is also consistent with the findings of the companion report studying moderately alcohol impaired young adults (Bruck, Thomas and Ball, 2007)

Evidence supporting this is the finding that the mean hearing threshold for a 500 Hz tone presented during the audiological screening test of participants (when awake) was lower than for 1000 Hz, 2000 Hz and 4000 Hz (with the latter having the highest mean) (see Section 4.1). Consistent with this are the hearing thresholds reported by Cruickshanks et al.1998 in their population-based study of 3,753 people aged 48-92 years where the average thresholds for the 500 Hz sound were almost always lower[22] than for 250 Hz, 1000Hz, 2000 Hz, 3000 Hz and higher frequencies.

It is not immediately obvious why square wave signals should be the most effective signals tested so far for waking people up. Square waves have been described as having a dissonant sound and the subjective "fullness" of the sound may give an impression of being louder (although this is not reflected in sound meter levels). It may be because human responsiveness to sounds while asleep is best when the signal includes a range of frequencies. If this were the case it would be expected that a voice alarm would be equally effective. Yet responsiveness to a voice alarm has yielded inconsistent results, with two studies suggesting it is equivalent in effectiveness to the 520 Hz square wave signal. These studies involved children (Bruck et al. 2004) and sober and alcohol impaired young adults (Ball and Bruck, 2004). However, the research using older adults (Bruck et al. 2006) found the male voice to be significantly less effective than the 520 Hz square wave.

Various researchers have considered the nature of the most effective alarms and/or ringer tones for alerting people who are awake. Patterson (1990) notes,

> Contrary to the general conception of pitch perception, we do not hear a separate pitch for each peak in the spectrum of a sound. Rather, the auditory system takes the information from temporally related components and maps them back onto one perception, namely a pitch corresponding to the fundamental of the harmonic series implied by the related components. This ….enables us to design warnings that are highly resistant to masking by spurious noise sources. (pg. 488)

The warning sound that Patterson advocates for the cockpit of a Boeing 747 is one with a series of harmonics that are at least 15 dB above the auditory threshold, which will vary

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[22] The only exception was a slightly lower average threshold for 250 Hz in the left ear in females (<1dB difference).

depending on background noise. A sound with four or more components in the appropriate level range is advocated as it is much less likely to be masked (Patterson, 1990).

Berkowitz and Casali (1990) tested the audibility of various ringer tones in both 20-30 year olds and 70-95 year olds and found that the "electronic bell" had the lowest audibility thresholds for both age groups. They attribute the advantage of this ringer to its prominent energy peaks between 1000 and 1600 Hz, with the less effective alternatives having more high frequency content. Their findings were consistent with an earlier report by Hunt (1970) who used the theory of critical band masking to predict the most effective telephone ringer tone. Hunt concluded that at least two spectral components between 500 and 4500 Hz were desirable to aid detection of a ringer above background noises. Moreover, Hunt cited an earlier research report by Archbold and colleagues (1967) that concluded that at least one of these components should be less than 1000 Hz. This conclusion would help those with age related hearing loss who generally have better hearing below 1000 Hz. These recommendations are all consistent with the spectral profiles of the square waves used (see Appendix F).

Given the above research, the results of the current study with hard of hearing adults are consistent with the idea that the most detectable signal when awake may also be the most alerting when asleep. This assumes that when we are asleep we arouse equally to all signals that we are capable of detecting, whether they are significant or not. Yet we know from previous sleep studies (e.g. Wilson and Zung, 1966) that this is not so, that we respond selectively to sounds we consider significant and are more likely to wake to those. In the testing situation of the current sleep studies the sleepers would be primed to awaken to any noise (indeed anything they could see, hear or feel) so all signals would be considered significant. However, in an unprimed home situation it is likely that only some sounds would be considered significant. Whether a smoke alarm sounding the T-3 signal would be interpreted as significant may depend on a wide range of factors, such as the number of other beeping noises in the environment (e.g. car alarms, trucks reversing), previous experience with smoke alarms and/or fire situations and/or regular education about alarm signals.

We are currently undertaking studies comparing signals with a range of pitches and patterns (including square waves with different frequencies) to determine their differential effectiveness in waking sober and unimpaired young adults. Ideally the best sound should also be tested in large numbers of unprimed sleepers in their own home environment.

Pillow and Bed shakers: The results show that 11.4% slept through all levels for the bed shaker and 3.3% slept through with the pillow shaker. If we consider how many hard of hearing adults would sleep through the shakers that are at the "off the shelf" intensity level (i.e. when purchased), the results suggest that for the bed shakers 20% would sleep through and for the pillow shakers 17%. These results are not inconsistent with the results reported by Murphy et al. (1995) where 30% of their hard of hearing adults slept through when the tactile signal was presented in slow wave sleep and 24% of their normal hearing participants slept through. In the Underwriters Laboratory (1991) research sleep stage was not controlled and it was found that 95% of legally deaf adults awoke to a tactile device (whether placed under the bed or under the pillow). In the Du Bois et al. (2005) study the results were reported as a composite across several sleep stages and 100% awakening with the intermittent vibrating bed shaker was reported in both hearing impaired and normal hearing adults (across all adult age ranges). Given that Du Bois et al. found that awakening with the continuous bed shaker was less (with only 82% of hard of hearing participants waking and 92% of the hearing able waking up at intensities as purchased), it seems reasonable to assume that waking efficacy in the current study would have been less if a continuous (rather than intermittent) bed shaker and pillow shaker had been used. Testing of the two tactile devices at their "off the shelf" intensity revealed that the bedshaker had a much stronger intensity (as indicated by the measured displacements) than the pillow shaker. It would be of considerable interest to test such a bed shaker in an under-the pillow placement and determine its waking effectiveness.

 It is hard to ascertain to what extent the differences across all the bed shaker studies may be due to the different devices used, sleep depth differences (which will vary across the night as well as with different adult ages), placement location of the device or perhaps even different hearing impairment criteria (including deaf versus hard of hearing). The conclusion from the current study is that, under the testing conditions, the two tactile

devices only awoke 8 out of 10 people with mild to moderately severe hearing loss at the "off the shelf" intensity levels. [23]

Strobe Lights: Although all intensity levels of the strobe lights were above the level as required in the standard (NFPA 72, 2002) it was found that only 27% awoke to the lowest intensity level. Thus the results show that under the testing conditions more than 70% of hard of hearing adults would sleep through a strobe light that was compliant with the standard. This result is consistent with the two studies using strobe lights which controlled for sleep stage (i.e. Bowman et al. 1995 and Du Bois et al. 2005) who both found that more than two thirds of their normal hearing participants slept through a strobe which was less intense than the lowest intensity level in the present study. The Du Bois study also tested hard of hearing adults with the strobe and found 66% slept through. The current results are not consistent with the studies by Nober et al. (1990) and Underwriters Laboratory (1991), neither of which controlled for sleep stage, although both used strobes of lower intensity than in the current study. While the latter study used deaf participants and reported 100% awakening, the former included both deaf and normal hearing participants and found 63% waking success with the normal hearing participants. Overall it seems that where strobes have been tested with sleep stage being assessed, their waking efficacy is poor. The findings of the current study certainly do not support the use of even very high intensity strobe lights to awaken sleeping participants who are hard of hearing.[24]

Comparison across all signals: The 520 Hz square wave was the single most effective signal, waking 92% at or below the benchmark (75 dBA) under the testing conditions. The bed and pillow shakers were about equivalent to each other, waking about 80-83% of the sample at or below their benchmark (i.e. the "off the shelf" intensity). They compared

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[23] In the companion report studying moderately alcohol impaired young adults (Bruck, Thomas and Ball, 2007), the two tactile devices were less effective at alerting participants than in the current study, with less than two thirds waking at the 'off the shelf" intensity level..

[24] This is consistent with the findings of the companion report studying moderately alcohol impaired young adults (Bruck, Thomas and Ball, 2007) where only a similar small percentage awoke to the lowest intensity strobe signal.

favourably to the current smoke alarm signal which could only wake 56% at or below the benchmark intensity. All signals performed much better than the strobe lights. For the strobe lights the lowest intensity presented was already above the level required in the standard, nevertheless only 27% awoke to this lowest intensity.

6.2 Signal onset versus signal onset

Where a signal was presented at a level that caused arousal, awakenings within 10 seconds of signal onset were found to be more common than at any other time, and this applied especially to the square wave sounds and tactile signals. After 10 seconds of a signal being presented some sensory adaptation may be occurring, reducing the chances of waking up as the signal continues. Other studies have reported that the chance of waking up in the first 30 seconds of a signal presentation are higher than subsequently (Bruck et al. 2004; Du Bois et al. 2005) but this is the first study that breaks awakenings down to within 10 seconds of signal onset.[25] The implications of this are that consideration should be given to inserting a pause after every two or three sets of the T-3 pattern (where each set is of 4 seconds duration). Exactly how long the pause should be would require further study. One example would be a continuous pattern of 12 seconds ON (three T-3 sets), followed by 12 seconds OFF, followed by 12 seconds ON etc. This finding also suggests that in studies of arousal thresholds to alarms it is ecologically more valid for the alarm to cut in from silence.

6.3 Sex and age differences

This study found no evidence of sex differences in responsiveness to any of the signals tested. Furthermore, perusal of the mean values of the Waking Scores showed no consistent direction of differences as a function of sex. Sex differences are rarely found in studies of arousal thresholds (Bruck, 2001; Bruck et al. 2006, Hasofer et al. 2005).

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[25] A similar pattern was founding the study using moderately alcohol impaired young adults (Bruck, Thomas and Ball, 2007).

It was found that the bed shaker was a significantly less effective alerting device for the 60+ age group compared to the group aged below 60 years. It is not immediately clear why this was so but it may have implications for any recommendations. It is possible that uncontrolled factors such as body mass, illness (e.g. diabetes) or medications (e.g. pain killers) may affect the responsiveness of the torso to tactile signals. In view of this the finding should be replicated with a sample closely screened for such variables to ensure the validity of the findings.

6.4 Behavioural Response Time

The results for the behavioural response time across the different signals confirmed the findings that were found using the EEG wakefulness (Waking Score) variable. When the data was further explored to determine whether it took participants a longer time to press the bedside button after EEG awakening to certain signals compared to others, no differences were found. If this variable is an indicator of sleep inertia, this data provides no evidence of a differential sleep inertia effect depending on the nature of the signal. What was of particular interest was the large individual variability but this was not the result of just a few individuals having consistently more sleep inertia for all signals. Several signals had maximum response delays of over a minute. It would be interesting to know the cause of the long delays and whether they had any implications for evacuation behaviour.

6.5 Signal combinations

There was evidence tentatively supporting the notion that different people will wake more readily to some types of sensory signals than others. The same participants tended to wake most readily to all three auditory signals and these people were a different group from those that woke more readily to tactile or strobe signals. Thus there is some support for the desirability of combining signals that alert different senses to maximise the chance of waking in populations that may be at risk for sleeping through an auditory signal. Given the waking effectiveness of the different alarms tested in this study the most effective combination for people with mild to moderately severe hearing loss is likely to be a low frequency square wave and a tactile alarm. Ideally this conclusion should be tested empirically. It is not known whether a synergistic effect of activating two signals simultaneously would occur or not.

6.6 Comparisons to field settings

In trying to extrapolate the percentages who awoke to each signal in this study, compared to what may be expected in the field for people who are hard of hearing there are several considerations.

A factor that would make it likely that more people would awaken in the field compared to in this study is related to *sleep stage.* This study has attempted to awaken people from their deepest stages of sleep. Slow wave sleep (SWS) occupies less than a quarter of normal adult sleep across the night (with the proportion decreasing with age). If signals occurred during other stages of sleep (i.e. stage 2 or REM) then arousal at a lower threshold would be expected (Zepelin, MacDonald and Zammit, 1984). However, deep sleep predominates in the early part of the night when most fire fatalities occur (Thomas and Brennan, 2002). In addition, with the total duration of sleep decreasing for many Americans (National Sleep Foundation, 2007) the proportion of their sleep that is deep sleep (SWS) is likely to be increasing, as sleep deprivation consolidates subsequent sleep. Higher auditory arousal thresholds have been shown to be associated with SWS rebound (Ferrara, De Gennaro, Casagrande and Bertini, 1999).

One factor that would make it less likely that people would awaken in the field compared to in this study is priming. All research participants were expecting to be exposed to various signals to test if this would awaken them. Previous work has shown that such an expectation, which increases signal meaningfulness, increases the likelihood of waking up. In one study priming increased the likelihood of waking up from 25% to 90% (Wilson and Zung, 1966).

In order to reduce the potential effect of confounding variables, the participants for a sleep study such as this are highly selected. Not only were the hearing criteria quite stringent, any adults that were taking medication affecting sleep were excluded, as were any reporting sleep difficulties. In addition, the participants were closely instructed to avoid certain factors that may decrease their chance of not waking up. These included prior sleep deprivation (including shift work) and alcohol consumption. In a field population

such confounding factors are likely to occur quite regularly and would increase arousal thresholds, especially in the first half of the night.

The factors exerting the strongest effects (priming and the screened/controlled sample) are likely to make any absolute values (such as sound levels, intensities and percentages responding to signals) underestimations. Thus any such extrapolations to residential populations must be done with caution. Notwithstanding this, as all the signals were tested under the same experimental conditions and in a way to minimize the uncontrolled effect of individual differences or night to night variations, *comparative* conclusions as to efficacy across signals can be expected to be valid.

6.7 Alerting Devices Questionnaire

This questionnaire found that around two thirds of the respondents wore hearing aids during the day and almost a half said they were not confident that a fire alarm signal would wake them at night. Disturbingly when it came to the provision for emergency notification during the night only one of the 44 respondents had either a non-auditory (sprinkler system) or specialist auditory alarm and 84% felt they did not need an alternative alarm (with many relying on their partners to wake them). Such complacency was found even though this sample may have been more sensitised to the issue, as all had volunteered to be part of this research and a few had been recruited through an organization selling alternative alerting appliances for the hearing impaired. Notwithstanding this, a number of participants said they were part of the research because they wanted to know if they needed one or not. It would be interesting to administer this questionnaire to a US sample to determine if the results are similar. Such results suggest that an educational campaign is needed if it is expected that hard of hearing people will purchase specialised devices for emergency notification. The most desirable option is that the most widely available "standard" audible smoke alarm for the overall population maximizes the chances of people who are hard of hearing waking through the optimal mix of pitch, pattern and volume. Given that (i) the US population is aging, (ii) that there are currently some 34.5 million people in the US who are hard of hearing, and (iii) that some 12% of people aged 45 years or more are unaware of their hearing problem (Cruickshanks et al, 1998) this issue is particularly important.

6.8 Conclusions and Recommendations

The main conclusions from this study are:

1. Under the testing conditions a 520 Hz square wave T-3 sound was the single most effective signal, awakening 92% of hard of hearing participants when presented at or below 75 dBA for 30 seconds and awakening 100% at 95 dBA. Both the 520 Hz square wave and the 400 Hz square wave were significantly more effective than the 3100 Hz pure tone T-3 sound, which awoke 56% at or below 75 dBA. In addition the 520 Hz square wave signal yielded the lowest hearing threshold when awake for this sample of people who were hard of hearing, from a set of eight alternative sounds with a range of pitch and patterns.[26]

2. Under the testing conditions the bed shaker and pillow shaker devices, presented alone, awoke 80-83% of the hard of hearing participants at the intensity level as purchased (vibrating in intermittent pulses).

3. Those hard of hearing participants who were aged 60 years or more were less likely to awaken to the bed shaker than those aged below 60 years. No age group differences were found for any other signal.

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[26] The efficacy of the 520 Hz square wave signal in arousing sleepers has now been demonstrated in children, sober young adults, alcohol intoxicated young adults (two studies), older adults and hard of hearing people. Furthermore in all these studies the high pitched alarm has been found to be the least effective of the auditory alternatives tested, in terms of waking people up.

4. Strobe lights, presented alone, were not an effective means of waking this population, with only 27% waking to the lowest strobe light intensity, which was more intense than that required by the standard (NFPA 72, 2002).[27]

5. There was tentative evidence that people may respond differently to different types of signals, suggesting that a bedroom alarm "kit" that combined two types of sensory signals (i.e. an auditory signal plus a tactile signal) may be more effective than one signal.

6. The results in this study are likely to be overestimations of the proportion of the hard of hearing population who may awaken to these signals in an unprimed, unscreened population, especially from deep sleep. Thus extrapolations of absolute intensities and percentages awoken in the study to the field should be made with caution.

7. It was found that, when a signal was presented at a level that caused awakening, most people awoke to the signal within the first 10 seconds of the signal being on. Thus it seems highly probable that a T-3 signal that is alternatively ON for about 10-15 seconds and OFF for a certain period of time (possibly of the same duration) will be more effective than a continuous sounding T-3 signal.

8. Questionnaire responses indicated a high level of misplaced complacency among people who are hard of hearing in terms of their need for specialist alerting devices. In view of this, and the fact that many people are not aware of their hearing loss, it is desirable that any standard audible smoke alarm for the general population emit a signal that maximises the chances of awakening for hard of hearing people (provided such a signal presents no increased risk to other sections of the population).

Recommendations:

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[27] This finding is consistent with the other two studies that have controlled for stage of sleep and tested the effectiveness of strobe lights in hard of hearing or normal hearing samples.

1. The technical feasibility of replacing the current high frequency smoke alarm T-3 signal with a low frequency square wave T-3 signal (with a fundamental frequency of 520 Hz or thereabouts[28]) for the entire population should be investigated as a matter of priority.

2. A suitable ON duration of such a T-3 signal appears likely to be in the range of 10-15 seconds, with the OFF duration tentatively suggested to be of similar duration but further research is required to determine this.

3. For this population of people with mild to moderately severe hearing loss the single best emergency alerting device is a low frequency square wave auditory signal and this is superior to bed shakers, pillow shakers and strobe lights, presented alone. Ideally this square wave signal should be as loud as possible. There is tentative evidence that combining a low frequency square wave with a tactile device may provide additional waking effectiveness.

4. Any recommendations for the use of strobe lights, presented alone, as an emergency alarm to awaken sleepers who are hard of hearing or of normal hearing should be withdrawn as soon as possible.[29]

5. Further study should be undertaken with people with hearing loss ranging from moderate to profound (i.e. including deaf people) to determine the best signals, or combination of signals, that will reliably awaken this population from deep sleep. This should include bed shakers, pillow shakers, low frequency square waves (beneficial for those with residual hearing) and could include strobe lights. In such research it would also be of interest to test bed shakers (vibrating in intermittent pulses) in an under-the-pillow placement.

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[28] We are currently undertaking a study with unimpaired young adults which will compare arousal to a 520 Hz square wave with other square wave signals with fundamental frequencies between 520 Hz and 2000 Hz.

[29] This recommendation should not be misinterpreted to apply to people who are awake or deaf people. Neither of these conditions were tested in this study or the companion report on the alcohol impaired (Bruck, Ball and Thomas, 2007).

6. Research on the efficacy of a range of different signals and signal combinations in different populations (e.g. with and without hearing loss) should also be conducted in a large number of home environments where the participants were not primed to expect a signal during the night and unscreened for factors such as medication or prior alcohol consumption.

7. There should be further investigation of an appropriate means of standardising the measurement of the intensity of bed and pillow shakers and this should inform a new standard.

7   References

Ahrens, M. (2004). U.S. experience with smoke alarms and other fire detection/alarm equipment. Quincy, MA: National Fire Protection Association.

Australian Standard (AS) 1670.4 (2004) *Fire detection, warning, control and intercom systems- System design, installation and commissioning.* Part 4: Sound systems and intercom systems for emergency purposes. Sydney: Standards Australia.

Australian Standard (AS) 1670.6 (2004) *Fire detection, warning, control and intercom systems- System design, installation and commissioning.* Part 6:. Smoke Alarms. Sydney: Standards Australia.

Australian Standard (AS) 2362.22 (1993) *Automatic fire detection and alarm systems - methods of test for actuating devices - sound pressure level test.* Sydney: Standards Australia.

Ball M and Bruck D (2004) The effect of alcohol upon response to fire alarm signals in sleeping young adults. In: Shields J. (Ed.). *Proceedings of the 3rd International Symposium on Human Behaviour in Fire*, Belfast, Interscience Communications, pp.291-302.

Ballard JE, T D Koepsell, et al. (1992) Association of smoking and drinking with residential fire injuries. *American Journal of Epidemiology, 135* (1), 26 - 34.

Berkowitz JP and Casali SP (1990) Influence of age on the ability to hear telephone ringers of different spectral content. *Proceedings of the Human Factors and Ergonomics 34th Annual Meeting.* Human Factors and Ergonomics Society, Santa Monica, CA. pp132-136.

Bowman SK, Jamieson DG and Ogilvie RD (1995) Waking effectiveness of visual alerting signals. *J Rehab Res & Dev*, 32 (1), 43-62.

Brennan P. (1998) Victims and survivors in fatal residential building fires. *Human Behaviour in Fire- Proceedings of the First International Symposium*, Fire SERT Centre, University of Ulster, pp. 157-166.

Brennan P and Thomas IR (2001) Victims of Fire? Predicting Outcomes in Accidental Fires, Second *International Symposium on Human Behaviour in Fire,* Boston, March, Interscience Publications, London.

British Standard BS 5446-3 (2005) Fire detection and fire alarm devices for dwellings – Part 3 Specification for smoke alarm kits for deaf and hard of hearing people.

British Standard BS 5446-1 (2000) Fire detection and fire alarm devices for dwellings. Specification for smoke alarms.

Bruck D (2001) The who, what, where and why of waking to alarms: a review. *Fire Safety Journal,* 36: 623-639.

Bruck D, Reid S, Kouzma J and Ball M (2004) The effectiveness of different alarms in waking sleeping children. *Proceedings of the Third Human Behaviour in Fire Conference,* Belfast, 1-3 October. London: Interscience Communications. pp 279-290.

Bruck D, Thomas I and Ball M (2007) Waking effectiveness of alarms (auditory, visual and tactile) for the alcohol impaired. Report for the *Fire Protection Research Foundation.*

Bruck D and Thomas I (2007) Comparison of the effectiveness of different fire notification signals in sleeping older adults *Fire Technology* (In press).

Bruck, D., Thomas, I. and Kritikos, A., (2006) Investigation of auditory arousal with different alarm signals in sleeping older adults. Report for the *Fire Protection Research Foundation.* Retrieved 23rd August 2006 from

http://www.nfpa.org/assets/files//PDF/Research/Investigation_of_Auditory_Arousal.pdf

Carter W (2003) *The Complete Home Guide to Medication.* Hinkler Press. Dingley: Australia.

Cruickshanks KJ, Wiley TL, Tweed TS, Klein BEK, Klein R, Mares-Perlman JA and Nondahl DM (1998) Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin: the epidemiology of hearing loss study. *Am J Epidemiol,* 148(9): 878-886.

Deafness Forum of Australia (2002) Submission to Standing Committee on Ageing Inquiry. Retrieved 9thMay 2007 from

http://www.aph.gov.au/house/committee/ageing/strategies/subs/sub66.pdf

Du Bois J, Ashley E, Klassen M and Roby R (2005) Waking effectiveness of audible, visual and vibratory emergency alarms on people of all hearing abilities. *Proceedings of the Accessible Emergency Notification and Communication: State of the Science Conference, Gallaudet University, Washington D.C. Nov 2-3, 2005.* Retrieved on 27th August 2006 from Http://tap.gallaudet.edu/EmergencyConf/Papers/Du%20Bois.htm.

Ferrara M, De Gennaro L, Casagrande M, Bertini M (1999) Auditory arousal thresholds after selective slow wave sleep deprivation. *Clinical Neurophysiology,* 110 (12), 2148-2158.

Hasofer AM, Thomas IR, Bruck D and Ball M (2005) Statistical modelling of the effect of alcohol and sound intensity on response to fire alarms. *Proceedings of the 8th*

International Symposium of the International Association for Fire Safety Science, Beijing, Sept 2005. pp. 507-518.

Hunt RM (1970) Determination of an effective tone ringer signal. *Preprint number 722 (M-5) from the 38th Convention of the Audio Engineering Society.* Audio Engineering Society. New York, NY.

ISO 8201(1987). Acoustics - audible emergency evacuation signal. International Organisation for Standardisation (ISO), Geneva, Switzerland.

Lee A (2005) The audibility of smoke alarms in residential homes. CPSC-ES-0503. US Consumer Product Safety Commission, Washington D.C. 20207-0001. February 2005.

Mitchell RE (2005) Can you tell me how many deaf people there are in the United States? Gallaudet Research Institute, Gallaudet University, Washington, DC. Accessed 27th April 2007 at https://gri.gallaudet.edu/Demographics/deaf-US.php

Murphy TI, Alloway CED, LaMarche CH, Bernstein DM, Ogilvie RD, MacLean AW and Jamieson DG (1995) How reliably does a vibro-tactile smoke alarm awaken individuals with hearing loss? *Sleep Research*, 24A (Abstract only).

National Fire Protection Association (NFPA) 72 (2002) *National Fire Alarm Code*. National Fire Protection Association, Inc. Quincy, MA.

National Sleep Foundation (2007) *2005 Sleep in America Poll.* Accessed 19th June 2007 at http://www.sleepfoundation.org/site/c.huIXKjM0IxF/b.2419039/k.14E4/2005_Sleep_in_America_Poll.htm

Nober EH, Well AD and Moss S (1990) Does light work as well as sound? Smoke alarms for the hearing impaired. *Fire Journal* (Jan/Feb), 26-30.

Patterson RD (1990) Auditory warning sounds in the work environment. Phil. *Trans. R. Soc. Lond.* B 327, 485-492.

Proulx G and Laroche C (2003) Recollection, identification and perceived urgency of the temporal three evacuation signal. *Journal of Fire Protection Engineering*, 13, 67-82.

Rechtschaffen,A. and Kales A (1968) *A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects.,* U. S. National Institute of Neurological Diseases and Blindness Neurological Information Network, Bethesda.

Underwriters Laboratories (1991) Report of research on emergency signaling devices for use by the hearing impaired (Subject 1971), Underwriters Laboratories, Northbrook, IL.

Underwriters Laboratories UL 1971 (2002) Standard for safety signaling devices for the hearing impaired. Underwriters Laboratories, Northbrook, IL.

US Census Data (2000) Table DP-1 Profile of General Demographic Characteristics Accessed April 27th 2007 at http://www.census.gov/prod/cen2000/dp1/2kh00.pdf

Wilson, W. P. and Zung, W. K. (1966). Attention, discrimination, and arousal during sleep. *Archives of General Psychiatry,* 15: 523-528.

Zepelin, H., McDonald, C. S. and Zammit, G. K. (1984). Effects of age on auditory awakening. *Journal of Gerontology*, 39(3), 294-300.

Appendix A: Measurement of the intensity of the bed and pillow shakers used in this project and shakers available commercially.

The intensity of the signal supplied by the pillow and bed shakers used in this project have been measured at the five levels used in the project and also in comparison with those of commercially available bed shakers obtained from the USA.

Characteristics of bed shakers (termed vibration units) are specified in UL 1971 but these do not seem to be relevant to pillow or bed shakers commercially available in the USA or Australia. There appear to be no standard requirements or test methods specified in standards in the USA.

A relevant test is specified in a British Standard, BS 5446-3:2005 Fire detection and fire alarm devices for dwellings - Part 3 Specification for smoke alarm kits for deaf and hard of hearing people (which we only became aware of towards the end of this project). The test specified in this standard appears to be relevant to the type of shakers commercially available and used in this project and appears likely to yield useful results for specification/comparison of bed and pillow shakers.

Unfortunately it has not been possible in the time available to comply completely with BS 5446-3. Some of the materials specified were not obtainable in Australia in the time available.

Nevertheless comparative testing of pillow and bed shakers used in the project and commercially available in the USA has been conducted complying as closely as possible with BS 5446-3:2005.

BS 5446-3 specifies that the vibration of an "integrator plate" be measured using an accelerometer when it is vibrated by a shaker embedded in a stack of specified plastic foam layers and with a "load plate" on the top of the stack (BS 5446-3, 2005).

Difficulties were experienced in applying this standard for a number of reasons. The first reason was the use of the T-3 pattern in activating the shakers. This means that the

shaker is only on for a brief period and there is a start up and wind down phase in each period (pulse). In comparison, when the shakers are run continuously the vibration becomes very regular and uniform. In the following comparison the average over one complete pulse was used as the basis for comparison, but there is some subjectivity involved in judging the start and finish of each pulse. A second reason was due to the method of generating the five voltage levels used to vary the intensity of the pulses from the tested shakers. This created a more complex vibration pattern than when the same shakers were driven by the devices with which they are normally supplied. This difficulty has lead to the comparisons being made using the measured acceleration rather than displacement specified in the standard, as it has proved difficult to satisfactorily obtain displacement measurements from the accelerometer.

Another problem is in comparing the shakers used in the project with shakers obtained from the USA and commercially available there.
(The five voltage levels were two levels below the specified voltage, the specified voltage and two levels above the specified voltage.)

The following procedure was used to obtain the comparative results below:
- the shaker was placed in the stack as specified in the standard
- the program used in the sleep testing was run and the acceleration measured at each intensity level (test mode)
- the shaker was then connected to the equipment with which it is normally supplied and used and the intensity measured (normal use)

The bed shaker used in this project were the "Vibes" bed shaker by Global Assistive Devices Inc. These are available in the USA and Australia.

The following average RMS accelerations were calculated based on the accelerometer data for the Vibes bed shaker at the five levels (low to high): 1.09, 1.56, 1.91, 2.10, and 2.41 ms^{-2}. In comparison when run using the normally supplied equipment the RMS acceleration was 1.76 ms^{-2}. Thus it can be seen that the middle level acceleration used in test mode (i.e. level 3) is just above the level measured for normal use (i.e. 'off the shelf").

The pillow shakers used in these projects were the "Visit" bed shaker by Bellman and Symfon AB of Sweden. These are available in Australia, but it is not known whether they are sold in the USA.

The average RMS accelerations calculated from the accelerometer data for the Visit pillow shaker at the five levels used in the projects were: 0.086. 0.187, 0.258, 0.294 and 0.533 ms^{-2} and this compares with an average RMS acceleration of 0.244 0 ms^{-2} when the pillow shaker is plugged into the Bellman Visit flash receiver, also by Bellman and Symfon.

This it can be seen that the third level is slightly above the strength of the pillow shaker when run using the equipment with which it is normally supplied.

Comparison of these shakers with shakers available commercially in the USA is difficult. The reason for this difficulty is that the shakers are highly non-linear in their response to varying input voltage. As a consequence, for valid comparisons, the voltage level supplied to the shakers when they are activated by the equipment that they are normally attached to is required. At this stage this equipment is not available and consequently the normal operation of these shakers cannot be monitored.

Appendix B: Measurement of the intensity of the strobes used in this project and strobes available as a fire alarm commercially

The strobe alerting signal is supplied by activating one, two or three strobes mounted at the end of the bed as shown in Appendix G and H. In the case of two and three strobes, the strobes were activated simultaneously.

The strobes used are not supplied with a specified intensity rating. There are two aspects of the strobes that are of interest. The first is the intensity of the flash compared with the intensity of the light produced by strobes used as fire alarm signals and as specified by standards. The second, of greater interest in terms of these projects, is the intensity of the light received at the pillow, as it is this that is likely to be of greater influence in determining the likelihood of response of sleeping people.

Both aspects are addressed in this appendix.

No absolute measurement of the intensity of the strobes has been undertaken. Instead samples of the strobes have been compared with commercially available fire alarm strobes of specified intensity obtained from the USA. The comparison was made by mounting the strobes in an identical position directed towards the light meter. The light meter was a Konica Minolta T-10 illuminance meter fitted with a sleeve and a filter to reduce the intensity of light received at the sensing device of the light meter so that the sensing device was not saturated by the flash. The filter was a Melles Griot filter of optical density 2.0. This test was conducted in one of the Sleep Laboratory bedrooms used several times in these projects with the light meter at the pillow and the strobes placed one meter away on the bed. The analog output from the light meter was captured on a Kikusui Digital Oscilloscope CDR5561U.
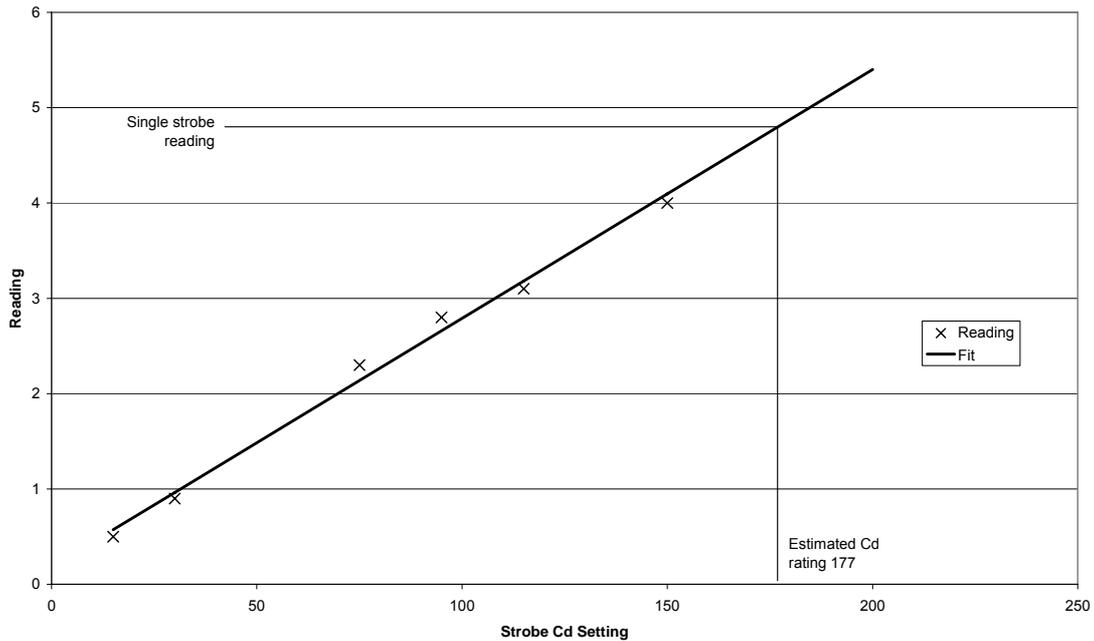
Figure B.1: Comparison of Strobes

A comparison of the relative intensity of the strobes used in this project compared with the Gentex Commander 4 24V Evacuation Signal is shown in Figure B.1. Very similar readings were obtained using several other commercially available strobes obtained from the USA. The candela rating of the Gentex Commander 4 is selectable at 15, 30, 75, 95, 115 and 150 cd.

It can be seen from this comparison that the single strobe light used in this project was of approximately 177 cd, assuming that the candela ratings of the Gentex Commander 4 strobe are accurate.

Measurements were also made of the relative intensity of the light received at the pillow when the strobe lights were in the specified positions at the end of a bed. The light from the flashes was reflected off several sheets of white bond paper placed on the edge of the pillow in the approximate position of a sleeping person's head. The reflected light was then received by the light meter mounted beside the middle flash. When commercial alarm strobes were used for comparison these were mounted directly in front of the middle flash of the three used in the project. The comparison between the strobes used in the project and the Gentex Commander 4 fire alarm strobe is shown in Figure B.2.
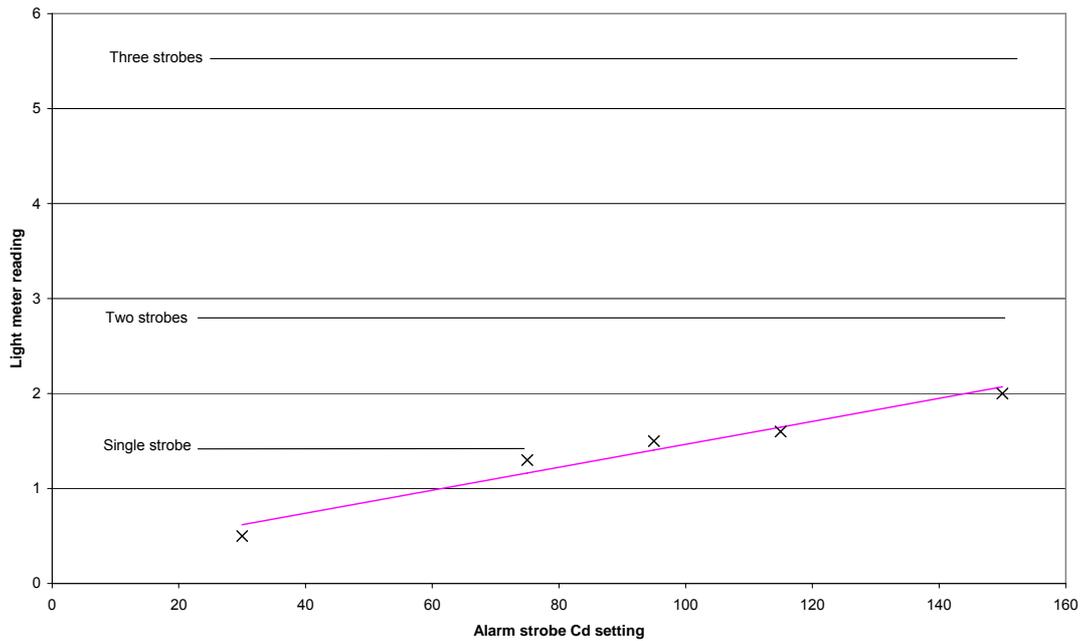
Figure B.2: Comparison of Light Intensity of Strobes at Pillow

The intensity of the flashes used in the project is not a linear relationship (number of strobes versus intensity) because the distance from the strobes to the pillow varied slightly with the top strobe (used as the single strobe) being the furthest from the pillow and the bottom strobe (used only when three strobes were required) being the closest.

It can be seen in Figure B.2 that the intensity with three strobes is almost three times the intensity of the most powerful commercial strobe (150 cd). Using this comparison it is estimated that the three strobes together emitted an intensity of about 420 cd.   Using the 150 cd strobe as the comparison point it is estimated from Figure B.2 that the two strobes together emitted an intensity of about 210 cd.

Appendix C: Advertisement placed in 26 local papers.

Appendix D.1: Table reproduced from Deafness Forum of Australia (2002) showing different categories of hearing impairment and their possible effects

Degree of Hearing Loss	Equivalent Decibel loss	Effects	Possible Hearing Augmentation Solutions
Normal Hearing	0 – 20 dB	No effects in good Listening environment	Good acoustical environment and amplification system
Mild Hearing Loss	25 – 30dB	Understanding speech can be difficult Has difficulty understanding in a noisy environment	Good acoustic environment And amplification system
Mild to moderate Hearing Loss	40 – 60dB	Has trouble hearing and understanding in Ideal conditions Unable to follow what is said in large open areas Hearing aids can assist	Good acoustical environment with amplification system an Induction loop or other assistive listening system ie. Infra red or radio frequency system
Moderate to severe Hearing loss	56 – 70dB	Communicates with Significant difficulty under all conditions Need visual clues. Hearing aids can assist but may still have poor clarity of speech	Good acoustical environment with amplification system and induction loop or other assistive listening systems ie. infra red or radio frequency system Clear speech or supplementary sign language assists
Severe Hearing Loss	71 – 90dB	Unable to hearing normal speech, depends on visual Clues (speechreading or sign language) Hearing aids assist with some speech sounds and identifying environmental sounds	Good acoustical environment with amplification and induction loop, or other assistive listening systems ie. infra red or radio frequency May require signing or deaf oral interpreter May require visual (text?) communication mode in noisy situations.
Profound Hearing Loss	91 dB +	Considered deaf May hear some loud sounds Does not rely on hearing as primary channel for communication May wear hearing aids to Assist with environmental & warning sounds and the rhythm of speech	Depends on a visual communication mode ie. speechreading ,sign language or a combination of both Requires signing or deaf oral interpreting and/or visual text system

Appendix D.2: Hearing thresholds (dB) for all participants across both ears and four frequencies as given by the hearing screening test.

L500	L1000	L2000	L4000	R500	L1000	L2000	L4000
45	45	55	75	35	40	55	60
60	65	60	45	60	55	55	30
50	35	30	35	35	35	35	40
25	25	25	55	25	25	25	35
40	20	20	35	40	20	20	35
55	50	40	40	65	60	45	35
55	65	60	45	50	60	55	60
65	50	55	85	20	30	25	20
50	65	60	65	50	80	85	65
55	45	55	50	45	45	50	65
40	45	55	70	40	30	45	70
20	15	35	55	15	15	25	35
25	25	35	40	20	30	40	50
30	25	30	35	30	40	30	40
30	30	25	15	40	30	20	35
10	10	10	75	20	15	15	75
40	45	40	45	40	40	35	45
55	50	50	55	45	40	45	40
50	65	70	50	65	65	65	60
50	55	80	80	45	65	90	80
55	65	30	25	80	70	70	60
50	60	55	55	70	70	40	60
25	25	20	40	35	35	25	40
50	40	25	20	45	45	35	30
35	30	40	45	25	35	45	50
35	40	60	65	30	30	50	65
25	30	40	45	25	35	35	50
15	10	20	35	30	45	65	85
20	30	50	50	20	30	50	50
35	30	70	55	25	40	60	50
30	30	40	70	70	70	50	30
25	50	65	90	35	55	65	60
40	40	40	45	40	40	40	45
10	10	20	65	15	10	25	60
40	60	65	60	40	65	70	75
25	30	25	50	25	30	25	50
40	50	70	75	35	55	65	60
55	50	60	65	35	40	50	50

Appendix D.3: Age categories of the participant sample and comparison with the US population for hard of hearing people (see also Table 2.1 in Section 2 of the main report)

age group	number in current study	number report being hard of hearing in US
15 - 44 years	13*	9.7 million
45-64 years	11	11.6 million
65+ years	14	13.2 million
Total	38	34.5 million

*all participants were over 18 years

Appendix E: Information about the Research Project

VICTORIA UNIVERSITY | **A NEW SCHOOL OF THOUGHT**

Title: Optimising fire alarm notification for the hearing impaired

At Victoria University our research team has, for several years now, been looking at the question of what smoke alarm signal is the best for waking up people. We have tested children, young adults (both sober and under the influence of alcohol) and the elderly and the results suggest that the current signal may not be as good as some alternative signals. This is especially important as we know that most fatal fires occur during the time when people are asleep and one in four fatal fires occur despite the presence of an operating smoke alarm. We would now like to investigate different types of signals that may be best for waking people with hearing impairments (ranging from mild to moderately severe). This includes low frequency beeps, strobe lights or pads (bed shakers) placed under the mattress or pillow that vibrate when there is a fire.

The overall study has two phases- an AWAKE phase and an ASLEEP phase.

AWAKE phase- In this phase a project officer will visit each volunteer in your their home at a time of mutual convenience. They will doing several things. First, they would like to complete a semi-structured interview about any devices in the home for informing occupants about the doorbell, phone and smoke alarm. If any non-auditory signals for this (e.g. strobe light), they will be interested to learn about how these devices are used and any preferences. They will also collect some basic information about the volunteer (e.g. age, living circumstances, job) and everyday hearing capabilities (with and without a hearing aid, if applicable). Second, they will test the volunteers (unaided) hearing to see if they meet the hearing criteria for participation in the ASLEEP phase. If the criteria are met they will play a series of eight different low frequency sounds to determine hearing thresholds for these sounds (also without a hearing aid).

ASLEEP phase- In this phase we will be presenting some different signals to volunteers while they are asleep in their own home. Equipment will be set up in the bedroom including a pillow shaker, bed shaker, strobe light, and speakers. The signals will be presented softly at first and then getting stronger because we are interested to know how strong each would need to be to wake people up. The strongest signals are still within safe limits. When the volunteer wakes up they will press a button by their bedside three times and then return to sleep. We will be presenting three signals a night and our previous experience suggests that people get very good at returning to sleep quite quickly. We want to always present the signals in the same type of sleep and because sleep changes across the night we will need to monitor the different stages of sleep of our volunteers. This is done by attaching ten small surface electrodes to the face and top of the head. A Sleep Technician (ST) is trained to do this and will present the signals from a hallway next to the bedroom. The gender of the ST will be matched with each participant for security purposes and all STs have passed a Police Check. The study will normally be conducted over two nights, with at least three nights between each individual study night to prevent volunteers being affected too much by sleep deprivation.

Each volunteer will receive a total of six signals during their sleep, normally three each night, thus two nights of sleep testing are involved. However, if a person has trouble returning to sleep after the first awakening or some other problem arises, we may need three nights. With each signal the volunteer will only need to press a button at their bedside to show that they have woken up. They can then return straight to sleep. After the final awakening for the night the electrodes will be removed and the Sleep Technician will depart.

As the study involves disruption to sleep, volunteers need to be aware that they may be sleepier than usual the next day and should be careful not to plan activities where sleepiness may be a problem. In particular the driving of a car should be avoided.

We are also asking all volunteers to moderate their consumption of alcohol immediately prior to a night's testing and on the night of testing. Also regular sleep/wake patterns should be maintained at these times to avoid sleep deprivation on the night of testing. Volunteers need to sleep on their own during the testing nights and notify any other members of the household that it is possible their sleep may be disturbed by sounds during the night (ear plugs will be made available on request). The study can be conducted at the VU Sleep Laboratory at St Albans campus for any reason, e.g. if the volunteer or any members of their household are concerned about sleep disturbance to those not participating.

Because we realise that being part of the ASLEEP phase of our study involves some inconvenience we are paying each volunteer $80 for each night of sleep testing. Because the design of our study makes it important for the same volunteers to complete all signals we will also be paying a $75 bonus on completion of all six signals. Thus the total payment for participation will be $235.

For this project we need volunteers who meet our selection criteria. These are:

- Aged from 18 to 80 years (inclusive).
- Believe they a hearing impairment that places them within the mild to moderately severely impaired category for both ears. Thus on the hearing screening test they will have a hearing loss of greater than 25 dBA and less than 71 dBA based on pure-tone average thresholds at 500, 1000, and 2000 Hz in each ear.
- Do not regularly take medication to help them sleep.
- Report that they do not have a sleep disorder and pass some simple questions exploring this.
- Report that they do not normally have difficulty falling asleep.

Your participation in this study will remain confidential and all data relating to your involvement will be identified by ID only. The cross-referencing of ID and name and address will be stored separately and securely.

Thank you for your interest in our research.

Contact regarding participation: Ms Samina Chea, on xxxxx. (Any other queries about your participation in this project may be directed to the researcher, Professor Dorothy Bruck - dorothy.bruck@vu.edu.au or xxxx)

If you have any queries or complaints about the way you have been treated, you may contact the Secretary, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4710

Appendix F: Spectral analyses of auditory signals used in the ASLEEP phase.

All the following signals were analysed spectrally as they were received at the pillow in a double bedroom measuring 3.6 m by 3.7m with a 3.6 m ceiling. The room had two windows and a single door. For the testing procedure both curtains were drawn and the door was closed.

DM 1585

Figure F.1: Spectral analysis of the 85 dBA 400 Hz square wave in the testing bedroom. The fundamental frequency was found to be approximately 402 Hz.

DM 1685

Figure F.2: Spectral analysis of the 85 dBA 520 Hz square wave in the testing bedroom. The fundamental frequency was found to be approximately 516 Hz.

DM 2385
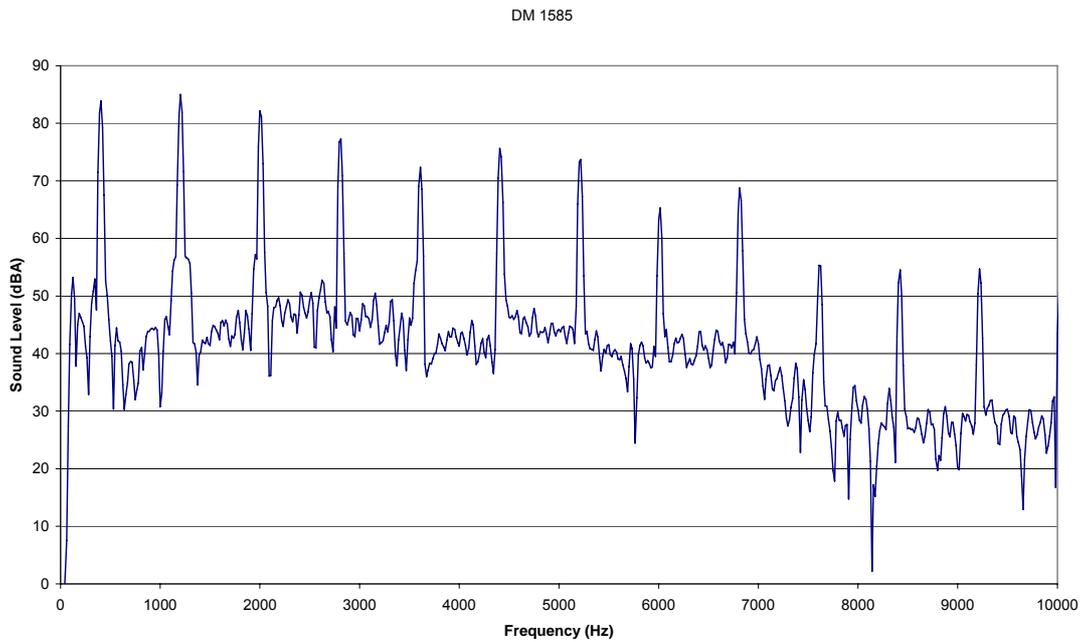
Figure F.3: Spectral analysis of the 85 dBA 3100 Hz pure tone in the testing bedroom. The fundamental frequency was found to be approximately 3110 Hz.
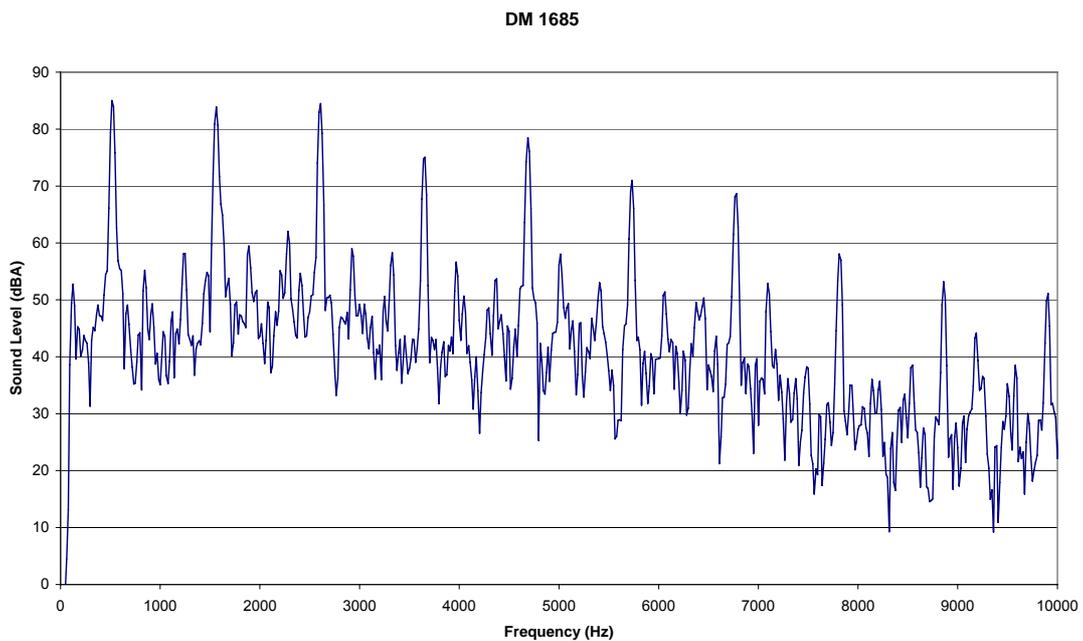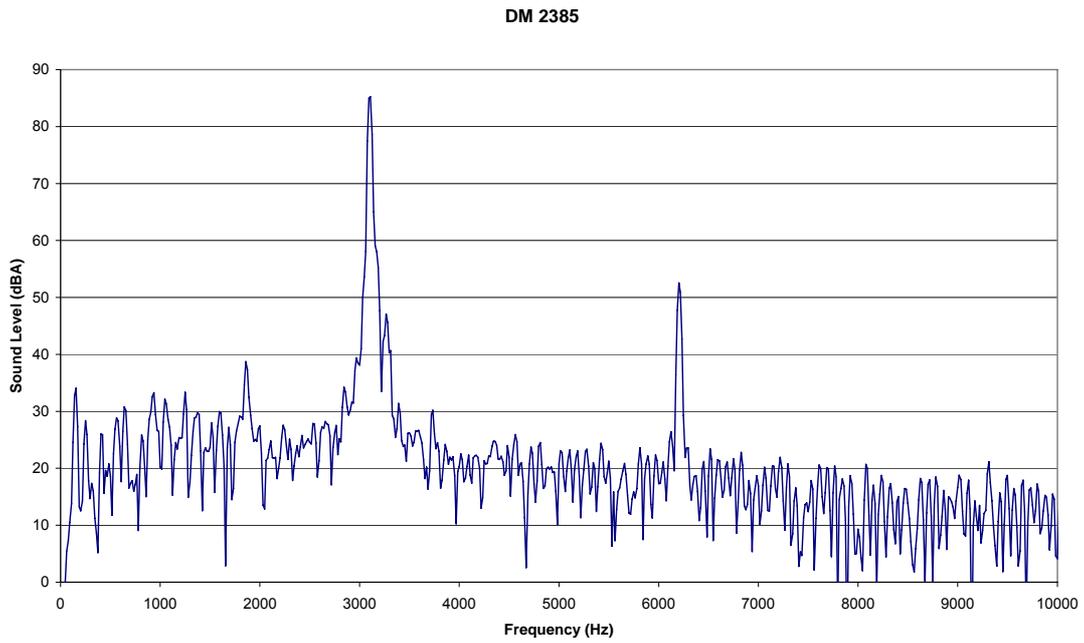
Appendix G: Photos of the strobe lights, bed shaker and pillow shaker

Strobe Lights

Bed shaker under mattress

Pillow shaker and linen bag for attachment under pillow

Appendix H: Strobe Alignment and Measurements

ID………………..Date………………… **Sleep Tech name**………………………..

Place strobe light stand at the foot of the bed. Each strobe should be aligned directly towards the edge of the pillow and should be in line with the centre line of the expected body position.

Measure and record

A   (height of the bed from the floor) _____mm
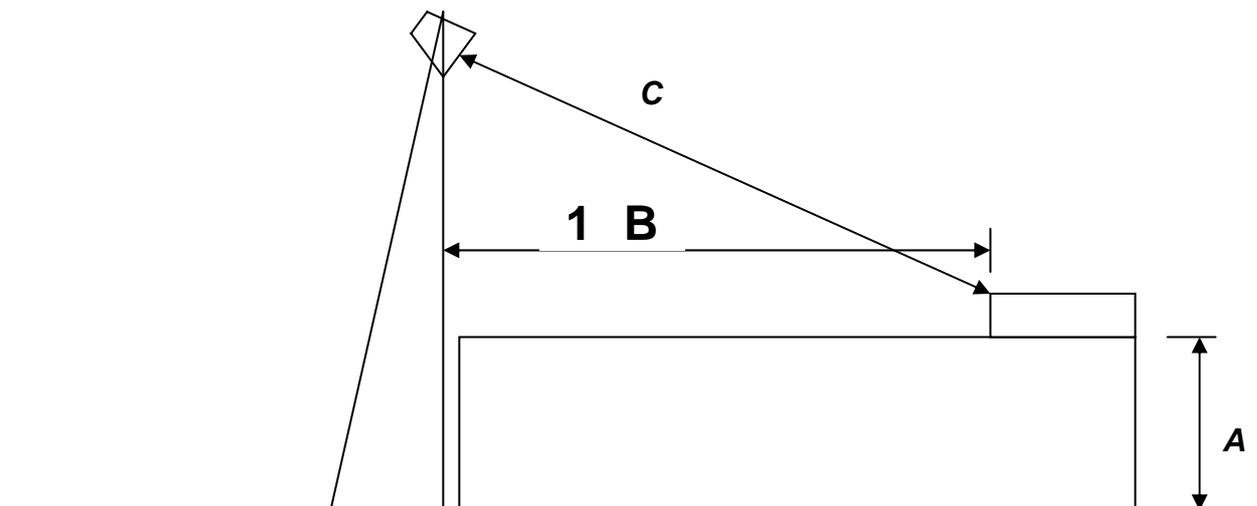
B   (horizontal measurement from edge of pillow to the strobe light stand)
      If possible make B = 1650 mm
           _____mm

C   (diagonal measurement from edge of pillow to middle of the TOP strobe light)
           _____mm

Appendix I: Sound measurement, calibration and signal delivery aspects

Speakers and Amplifier used for sound delivery: Kevlar Car speaker, 40 Watts RMS (Response Precision Brand) and Hylex PA Amplifier PA-50W

Sound meter type: Lutron Model SI-4001 (2) both recalibrated prior to the study, using signals in the range of 80-130 dB, dBA and dBC, and frequencies of 244 Hz-1000 Hz .

Creation of sound files: For the sound delivery program it was necessary to have sound files of each signal at levels from 55 dBA to 95 dBA in 10 dBA increments. This was done in a sound attenuated TV studio at a Victoria University campus.

Once a signal was available at a particular volume it was played through the speakers to be used in the study and the decibel level adjusted using acoustic software (Sound Forge 6) so that it was measured to be received at a particular volume (eg 55 dBA) as assessed by the sound meter. A tolerance range of plus or minus 1 dBA was allowed. Table G.1 shows the sound meter settings.

Table C.1: Sound meter settings for creating the different sound files.

Meter settings	For recording of the following sound files
30-80 dBA	35-60 dBA inclusive
50-100 dBA	65-85 dBA inclusive
80-130 dBA	90-94 dBA inclusive

Thus for each of the sounds, sound files at different volumes were created. The settings on the sound meter were "slow response" and "maximum hold" for all sound level assessments. The volumes would fluctuate but the most dominant level was used.

Calibration in bedrooms: The procedure to be followed in the bedrooms of participants was as follows: The 520 Hz square wave T-3 75 dBA sound file was played from the speakers, which were located approximately one metre from the pillow, where the sound meter was placed. The volume knob on the speakers were adjusted so that the sound level meter was showing as close as possible to 75 dBA (using all the settings as above).

Appendix J: Screening questionnaire re sleep deprivation and alcohol

Please complete this questionnaire <u>prior</u> to preparation for the sleep study.

ID Number _____

Please circle one: Night 1   Night 2   Night _____

1. Thinking about your sleep last night, compared to your usual sleep, was it: (please circle <u>one</u> of the options)

Much better than usual

A little better than usual

Same as usual

A little worse than usual

Much worse than usual

2. If you chose "much worse than usual", please comment on why your sleep was much worse. (Otherwise leave blank)

3. Have you consumed any alcohol since 4pm today? If so, please describe the type (beer, wine etc), the quantity and the time of day when it was consumed.

Type:

Quantity:

Time of Day:

In this research we are keen for your sleep to be as similar as possible on the different nights of the study. Two factors that can especially affect your ability to wake up are
If you are quite sleepy from having had poor sleep on the previous night, or, if you have consumed more than a glass or so of alcohol close to bedtime
If you think these may be of concern please discuss this with the Sleep Technician.

Thanks

Appendix K: Questionnaire on alerting devices

Administered by: _____

ID:_____   Today's Date: _____

Current age:_____   Sex: *Male/Female*

Do you live alone? *Yes/No*

To your knowledge since what age have you had a hearing impairment? (Estimate if necessary.)
_____

During the day. Please answer these questions in relation to your normal daytime activities. Feel free to add comments.

1. If you own a hearing aid, do you wear it when <u>outside the home</u>? A*lways /Sometimes/ Never/ Not Applicable (circle)*

2. Do you wear a hearing aid <u>at home</u>? *Always/ Sometimes/ Never/ Not Applicable (circle)*

3. When at home do you normally rely on your hearing alone for knowing when someone is at the <u>front door</u>? *Yes/ No (circle)*
    - If yes, how confident are you that you will hear it? V*ery/ somewhat/ not at all (circle)*

4. When at home do you normally rely on your hearing alone for knowing when your <u>telephone</u> is ringing? *Yes/No (circle)*
    - If yes, how confident are you that you would hear it? V*ery/ somewhat/ not at all (circle)*

5. When at home during the day do you rely on your hearing for knowing if there was a <u>fire emergency</u>? *Yes/No (circle)*
    - If yes, how confident are you that you would hear a fire alarm? V*ery/ somewhat/ not at all (circle)*

6. If you have had any relevant experiences involving a <u>fire alarm sounding during the day</u> (e.g. false alarms) please describe them (e.g. Did you hear it easily? How far away from the alarm were you? Were you wearing a hearing aid?)

During the night when in bed. Please answer these questions in relation to being in bed at night. Feel free to add comments.

7. Do you wear a hearing aid when sleeping? A*lways /Sometimes/ Never/ Not Applicable (circle)*

8. When at home do you normally rely on your hearing for an <u>alarm clock</u> to wake you in the morning? *Yes/ No (circle)*
   - If yes, how confident are you that you will hear it? V*ery/ somewhat/ not at all (circle)*

9. At night in bed do you normally rely on your hearing alone for knowing when someone is at the <u>front door</u>? *Yes/ No (circle)*
   - If yes, how confident are you that you would wake up to it? V*ery/ somewhat/ not at all (circle)*

10. At night in bed do you normally rely on your hearing alone for knowing when your <u>telephone</u> is ringing? *Yes/No (circle)*
    - If yes, how confident are you that you would wake up to it? V*ery/ somewhat/ not at all (circle)*

11. At night in bed do you rely on your hearing alone for knowing if there was a <u>fire emergency</u>? *Yes/No (circle)*
    - If yes, how confident are you that you would wake up to a fire/smoke alarm? V*ery/ somewhat/ not at all (circle*)

12. If you have had any relevant experiences involving a <u>fire alarm sounding at night</u> (e.g. false alarms) please describe them (e.g. Were you asleep? Do you think you woke up straight away? Were you told you slept through it? How far away from the alarm were you? Were you wearing a hearing aid?)

Alternative Alerting Devices for a Fire Emergency

This next section is about any devices in the home that provide a <u>non-auditory signal</u> to alert you in case of a <u>fire</u> (e.g. a flashing light, vibration).

13. Do you have such a non-auditory device for a fire emergency? (Please tick one)

   ☐ Yes - *please answer question 14.*

   ☐ No - *please answer questions 15-17.*

Question 14 is for those with an alternative signal fire/smoke alarm:

14. How do you become aware that the fire alarm is activated? *Please describe:*

- How confident are you that this would alert you during the day?
V*ery/ somewhat/ not at all (circle)*

- How confident are you that this would alert you at night when asleep?
V*ery/ somewhat/ not at all (circle)*

- How can you tell the difference between the fire alarm signal and a signal for any other device (e.g. alarm clock/ telephone/doorbell)?

15. If you have had any relevant experiences while asleep (e.g. false alarms) please describe them (e.g. Do you think you woke up straight away? Were you told you slept through it?)

Questions 15-17 are for those who do NOT have an alternative alerting device for a fire emergency during sleep.

16. In the past, have you felt the need for an alternative fire alarm when sleeping that does NOT use sound? (Tick one)

 ☐ Yes – *please answer Question 17.*

 ☐ No - *please answer Question 18.*

17. If <u>yes</u>, what has prevented you from installing such a device?
    (Tick the ONE that is the most applicable.)

    ☐ Cost

    ☐ Intend to but haven't got around to it

    ☐ Hard to set up

    ☐ Don't know where to get them from

    ☐ Not an important enough need

    ☐ Other (comment) _____

18. If <u>no,</u> why have you NOT feel the need for such an alternative alerting fire emergency device? (Tick the ONE that is most applicable.)

    ☐ Confident the sound of a fire/smoke alarm would awaken me

    ☐ Have not thought about it before

    ☐ Rely on another person in the house to alert me

    ☐ Very unlikely to need a fire alarm

    ☐ Other (comment) _____

Appendix L: Details of stage of sleep when different signals were presented.

(See also Section 5.9)

Table L.1: Percentage data of stages of sleep when signal was presented, as a function of signal type, sex and age group.

	Stage 2	Stage 3	Stage 4	Total SWS
400Hz square	6.3	37.5	56.3	93.8
520Hz square	9.4	34.4	56.3	90.7
3000Hz pure	0.0	33.3	66.7	100.0
Pillow Shaker	7.1	14.3	78.6	92.9
Bed Shaker	6.5	29.0	64.5	93.5
Strobe	8.8	32.4	58.8	91.2
SEX				
Male	9.0	30.8	60.3	91.1
Female	4.7	30.2	65.1	95.3
AGE GROUP				
Under 60	1.1	22.3	76.6	98.9
60 +	12.2	38.9	48.9	87.8
OVERALL	6.5	30.4	63.0	93.4

Overall 93.4% of all signal presentations were in SWS. In the above table (Table L.1) it can be seen that the group most likely to be awoken from stage 2 were males aged over 60 years and this demographic is well known to have the least amount of SWS (Ohayon et al. 2004). There were no signal presentations for the 3100 Hz signal from stage 2, whereas there were for all the other signals. Given that high thresholds were found for this signal it was important to determine whether these thresholds may be significantly influenced by this sleep stage bias. Thus a series of non-parametric analyses were computed for each signal using sleep stage as the independent variable. For all signals except the 3100 Hz signal there were three groups (i.e. three sleep stages) to compare

and thus a Kruskal Wallis Test was used. For the 3100 Hz signals there were only two groups and thus a Mann Whitney U test was used. The mean values and results are presented in Table L.2.

Table L.2: Waking scores as a function of signal presented and stage of sleep in which the signal was presented.

signal	stage 2		stage 3		stage 4		non-parametric test*	
	n	mean	n	mean	n	mean	value	p
400 Hz square wave	2	1.0	12	3.3	18	2.9	1.6	.45
520 Hz square wave	3	1.7	11	1.5	18	3.2	2.6	.27
3100 Hz pure wave	0	0.0	9	5.2	18	6.4	63.5	.36
bed shaker	2	2.0	9	2.7	20	4.4	1.3	.52
pillow shaker	2	1.0	4	2.0	22	3.5	.96	.62
strobe	3	8.3	11	7.3	20	10.1	7.4	.024

* See text for details of which non-parametric test was used.

Because the cell numbers in some cases are small some caution needs to be exercised in interpreting the results shown in Table L.2. The analyses found no significant differences in Waking Scores across the sleep stages for any signals except the strobe lights, where p=.024. The mean values suggest that this difference is due to the larger Waking Score mean value for stage 4, and not because of a substantial difference between stage 2 and stage 3. Inspection of mean values reveals that this interpretation holds across all the signals. Thus it can be concluded that the pattern of results does not suggest that the data is flawed because no awakenings were from stage 2 for the 3100 Hz signal.