Optimizing Fire Alarm Notification for High Risk Groups Research Project

Waking effectiveness of alarms (auditory, visual and tactile) for the alcohol impaired

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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, Ian Thomas and Michelle Ball 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 the alcohol impaired

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1 Executive summary

Studies of fire fatalities in the US, UK and Australia across young and middle aged adult groups (e.g. 18 to 65 year olds) have consistently shown that alcohol impairment is a key factor in over half of the fire fatalities. One recent study (Ball and Bruck 2004a), using a small sample of young adults, found that the ability to awaken to an auditory alarm was significantly reduced by alcohol intoxication. Furthermore the data suggested that the current high pitched alarm was not as effective at waking this population under sober or alcohol impaired conditions as the alternative auditory signals tested. Other studies, using children and older adults (sober) have also found that the high pitched alarm was not as effective at waking up occupants. In all cases to date an auditory signal called the “mixed T-3” has been found to be the most effective auditory signal for arousing sleepers across a range of age groups. This mixed signal is a square wave with a fundamental frequency of 520 Hz,[1] presented in a Temporal 3 (T-3) pattern.

In the light of these findings it became important to investigate responsiveness to a range of alternative auditory signals, including a 520 Hz square wave, in a larger sample of sleeping adults who were impaired by alcohol. A further question of interest was whether non-auditory signals, such as strobe lights and bed shakers, would actually be more effective at awakening sleepers under the influence of alcohol than auditory signals. This study addresses these issues.

Thirty two young adults aged 18 to 26 were each exposed to a range of signals across two nights during deep sleep (stage 4). Prior to sleep all had consumed alcohol such that their blood alcohol concentration (BAC) was measured at .05. Seven signals were tested:

- 400 Hz square wave signal in T-3 pulse
- 520 Hz square wave signal in T-3 pulse
- 500 Hz pure tone in T-3 pulse

[1] Square waves have, in addition to their fundamental frequency, additional peaks at the 3rd, 5th, 7th etc harmonics.

- 3100 Hz pure tone in T-3 pulse
- Bed shaker- under mattress – T-3 pulse
- Pillow shaker – T-3 pulse
- Strobe light - T-3 pulse (modified)

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 the maximum intensity was reached, or the participant awoke.

The main conclusions from this study are:

1. Some auditory signals are an effective means of waking moderately alcohol impaired (.05 BAC) young adults from deep sleep. Two signals, the 400 Hz and 520 Hz square wave T-3 sounds, were significantly more effective than the 3100 Hz pure tone T-3 sound.

2. Under the testing conditions a sound level of 75 dBA at the pillow was sufficient to awaken this population using either of the two square wave sounds. These signals awoke 93-100% of participants at 75 dBA or less. In contrast, the 3100 Hz signal awoke only 61.5% of the moderately alcohol impaired participants.

3. The bed shaker and pillow shaker devices tested were not an effective means of waking moderately alcohol impaired young adults from deep sleep, either at the intensity level as purchased, or at higher intensity levels. Only 58%-64.5% awoke at the intensity level as purchased.

4. Strobe lights were not an effective means of waking this population, with only 24% waking to the lowest strobe light intensity, which was more intense than that required by the standard (NFPA 72, 2002).

5. The results in this study are likely to be overestimations of the proportion of moderately alcohol impaired young adults 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.

6. It was found that, where 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 signal that is alternatively on and off for this period of time will be more effective than a continuously sounding signal.

Recommendations:

1. That bed shakers, pillow shakers or strobe lights, presented alone, should *not* be considered as an alternative emergency alarm for people with normal hearing.

   This recommendation is made on the basis that across the population a proportion of people sleep after having consumed alcohol, and visual and tactile signals will be less likely to awaken them than auditory signals. Furthermore, it is possible that the findings with alcohol can be generalised to other types of sedating chemicals (e.g. hypnotic medication).

2. That further research be conducted to determine the nature of the best auditory signal (both in terms of spectral characteristics and on/off timing) to replace the current high pitch alarm.

   A square wave sound with a fundamental frequency in the lower ranges (i.e. 520 Hz) has now been consistently documented to be more effective than the current high pitched smoke alarm signal across a range of populations (children, older adults, sober young adults, alcohol impaired young adults and adults who are hard of hearing[2]). A signal that has an ON-OFF sound pattern of about 10-15 seconds may be more effective than a continuous signal.

[2] Readers may find the companion report, Bruck and Thomas (2007b) *Waking effectiveness of alarms (visual, auditory and tactile) for adults who are hard of hearing,* of interest.

2 Review of the Literature

2.1 Alcohol and fire fatality

In usual circumstances most unimpaired adults respond well to smoke alarm signals that are installed and operated within prescribed standards. Yet examination of fire fatality statistics from around the developed world reveal that being asleep in a residential home is a serious risk factor for death in a fire (Barillo & Goode, 1996; Brennan, 1998; Karter, 1986; Runyan, Bangdiwala, Linzer, Sacks & Butts, 1992).

Clearly, it is not always simply being asleep that increases a person's chances of dying in a fire. International studies have examined the risk factors for death in a fire and found that age is an important factor, with very young children and the elderly being the groups most at risk (Barillo & Goode, 1996; Brennan, 1998; Karter, 1986; Marshall, Runyan, Bandiwala, Linzer, Sacks & Butts, 1998; Runyan, Bangdiwala, Linzer, Sacks & Butts, 1992; Sekizawa, 1991). The reasons for the increased vulnerability of people in these age groups are largely intuitive. It is obvious that the very young and the very old are likely to have less capacity to respond to a fire emergency due to factors such as reduced physical and cognitive resources. Moreover it has been shown that the presence of an adult who is neither affected by physical or cognitive impairment nor under the influence of psychoactive substances increases the chance of survival for people in these vulnerable age groups (Marshall et al., 1998).

Careful examination of data for people aged between 18 to 64 years shows that alcohol is consistently implicated as a factor that significantly elevates a person's risk for death in a fire. In fact presence of alcohol in the system has been found to elevate this risk factor to the extent that it matches the risk factor for the most vulnerable age groups (TriDataCorporation, 1999). Furthermore, alcohol impairment has also contributed to the number of deaths that occur in children and the elderly. For example Marshall and colleagues (1998) reported that surviving carers were affected by alcohol in 15% of related juvenile deaths. Most importantly, alcohol impairment has been found to greatly increase the probability of death from fire across *all* age groups to the extent that it has cited as the *single most significant risk factor* (Runyan et al., 1992).

International studies reporting examination of fire fatality statistics that have identified alcohol as a significant risk factor for death in a fire include the following:

1. Berl & Halpin (1978) examined data for fire deaths in the state of Maryland, USA for the period 1972 to 1977. They found that 50% of victims aged over 20 years showed a blood alcohol content (BAC) of above .10, classifying them as legally intoxicated. Further examination showed that approximately 70% of persons in the age group 30 to 60 years were legally intoxicated at the time of their death. This is interesting because fire fatalities are actually lower for people in that age group, meaning that alcohol ingestion greatly increased the risk factor for death in the population studied.
2. Patetta & Cole (1990) conducted a study examining coronial data for deaths resulting from fire in North Carolina, USA, during 1985. They reported that 56% of victims tested for the presence of alcohol were legally intoxicated (≥.10 BAC at that time).
3. Barillo & Goode (1996) conducted a study of fire deaths in New Jersey, USA, covering the seven year period from 1985 to 1991. They reported that alcohol was detected in the system of 29.5% of fire victims.
4. Squires & Busuttil (1997) conducted a study of the association between alcohol and fire fatalities in Scotland, UK, for the period 1980 to 1990. Their data showed that alcohol was present in the systems of 62% of fire victims.
5. Brennan (1998) examined coronial data of 150 fire fatalities that occurred in the state of Victoria, Australia from mid-1990 to 1995. Blood assay results were available for about 70% of victims. Of those aged between 18 and 75 years, over half showed a BAC in excess of .10.
6. Marshall, Runyan, Bangdiwala, Linzer, Sacks & Butts (1998) examined data collected by the medical examiner of North Carolina, USA, for fire deaths from 1988 to 1999. Of the cases where tests for alcohol were conducted, 53% showed a BAC exceeding .10.
7. McGwin, Chapman, Rousculp, Robison & Fine (2000) examined data of fire fatality victims in the state of Alabama, USA, for the period 1992 – 1997. They reported that over half of all victims tested positive for alcohol.
8. Sjögren, Eriksson & Ahlm (2000) investigated data for all unnatural deaths in Sweden from 1992 to 1996. Their results showed that 41% of all fire deaths were associated with alcohol use.

9. In an unpublished thesis that examined coronial data for fire deaths in Victoria, Australia for the period 1998 to 2005, Watts-Hampton (2006) reported that 75% of fatalities had positive results for alcohol and/or drugs in their system.

It is worth noting that the figures reported above may well represent an underestimation of the effects of alcohol. Firstly, blood tests are not completed as a matter of routine in all jurisdictions, or for all cases within a jurisdiction. This means that alcohol data is often reported on a subset of the completed database. Secondly, only the blood alcohol content of the victims themselves is reported. The figures fail to account for deaths that occur as a result of carers of small children or incapacitated older persons being under the influence of alcohol.

Although sex differences were not investigated in all of the studies, there is a mounting body of evidence to suggest that males who die in a fire are more likely to have alcohol in their systems than females. Berl & Halpin (1978) reported that the overall death rate for males outnumber females by 50%. They claimed that this was mainly due to the effects of alcohol, with males accounting for 66% of all intoxicated cases. Squires and Busuttil (1997) reported that 68.4% of male victims tested were found to have consumed alcohol compared to 54.3% of females. Further examination revealed that 63.3% of male fatalities and 48% of females tested had a BAC in excess of .08. Watts-Hampton (2006) reported that 63% of victims who displayed a BAC in excess of .10 were males. Finally, Sjögren and colleagues (2000) reported that unnatural deaths associated with alcohol were more than twice as likely in males, which included but does not specifically pertain solely to, death in a fire.

Another important interaction with alcohol relating to elevated risk for death in a fire is cigarette smoking. In their review of English language studies spanning the years from 1947 to 1986, Howland & Hingson (1987) stated that eight of nine coronial studies sighted indicated that alcohol was more likely to be found in the systems of victims of fire that was ignited by cigarettes. Other studies have similarly reported alcohol and cigarettes to be a lethal combination to the extent that the majority of smoking related fire fatalities show some direct connection with alcohol consumption (Patetta & Cole, 1990; Ballard & Koepsell, 1992; Brennan, 1998; Watts-Hampton, 2006).

It is relatively simple to make the connection between alcohol intoxication and death in fire through the examination of blood assay results of victims. However without eyewitness accounts, it is less easy to determine in what way the alcohol affected the person's ability to survive. The physiological effects of alcohol are well documented, and a relationship between alcohol intoxication and overall chance of suffering accidental injury or death is firmly established. The effects of alcohol may elevate the risk for death or injury in a fire in the following ways:

- by affecting a person's ability to perceive the signal coming from a smoke alarm
- by affecting their ability to correctly interpret the alarm signal once it has been heard
- by reducing the effectiveness of cognitive processing, thereby increasing the chance of an inappropriate response, such as failure to avoid a dangerous pathway
- by adversely affecting motor functioning, for example causing poor balance and coordination which can impair and reduce the effectiveness of escape behaviour
- by impairing the recovery from burns, with this being significantly worse for alcoholics, meaning that they may suffer death from more minor injuries than non-alcoholics.

2.2 Alcohol, auditory alarms and sleep

Unfortunately there is limited research on how arousal thresholds during sleep may differ with alcohol ingestion. Some studies have tried to document possible changes in the amount of deep sleep during the night but consistent differences are not reported, possibly because a 'whole of night' approach tends to be used. Where changes *across the night* are considered it has been shown that deep sleep (also termed slow wave sleep or stages 3 and 4) is often increased in the first two hours of sleep (Landolt, Roth, Dijk and Borbely, 1996) and decreased in the latter part of the night (Stone, 1980) As time of day fire fatality statistics suggest that midnight to 2 am is associated with more fire deaths at home this initial augmentation of deep sleep is likely to be of most significance in terms of responsiveness. In non-REM sleep (which includes deep sleep) changes in the EEG power density after alcohol ingestion have been noted. Increases at both the high frequency levels (associated with waking behaviour) and low frequency delta waves (associated with deep sleep) have been reported (Dijk, Brunner, Aeschback, Tobler and Borbely, 1992; Landolt et al. 1996). It is difficult from these architectural changes in EEG sleep to accurately predict how responsiveness to a signal across the night may be altered at different levels of intoxication and different times of the night. The reduced waking activity and initial increase in deep sleep suggest an overall reduced responsiveness, especially in the early part of the night.

A study undertaken by Ball & Bruck (2004a) specifically explored the effect of alcohol on the ability of young adults to awaken to a range of auditory signals in three conditions, sober, .05 BAC, and .08 BAC. Figure 2.1 shows the results that were obtained with 12 participants under the different BAC conditions with three different auditory alarm signals. The participants were aged 18 to 26 years and were self-reported deep sleepers. The methodology involved presenting signals in stage 4 sleep (the deepest stage of sleep) at volumes increasing in 30 second steps of 5 dBA each from 35 dBA to 95 dBA, with no silences between the steps. Responsiveness to the female voice alarm and the mixed T-3 (which was actually a square wave with a fundamental frequency of 520 Hz) was very closely matched across all three levels of alcohol intake and both performed significantly better than the high pitched alarm, which was a 4000-5000 Hz continuously beeping smoke alarm signal, as found in older alarms (i.e. not a T-3 pattern). It was found that alcohol significantly affected the ability of the sleeping participants to respond to all alarm signals.

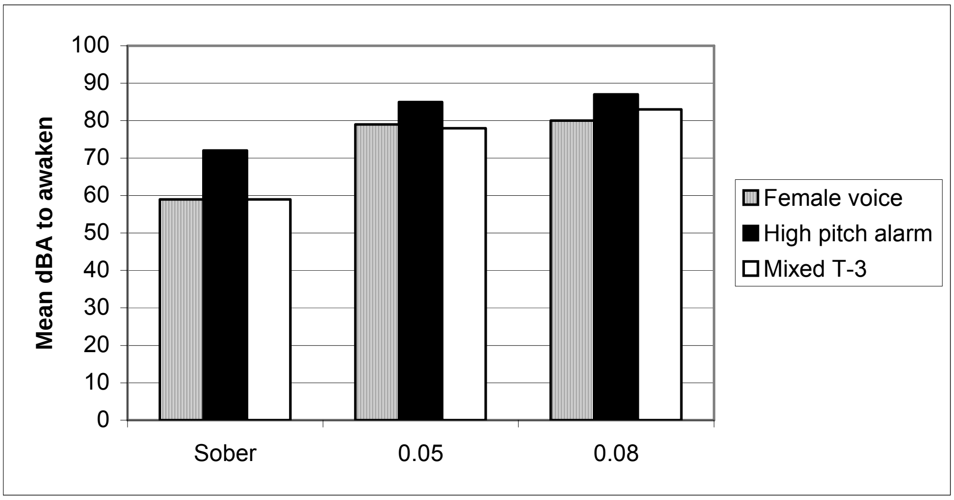

Figure 2.1: Comparison of the mean dBA levels of different alarms required to awaken young adults under different blood alcohol content conditions (n=12). Data from Ball and Bruck 2004a.

Sex differences were also explored with no significant results. However a later paper used the same data in a stochastic model designed to estimate the probability of a delayed response. It was found that alcohol lowered the probability of recognition of an alarm signal in both sexes, but that males show decreased sensitivity to auditory alarms in both sober and alcohol conditions (Hasofer, Thomas, Bruck & Ball, 2005).

The Ball and Bruck (2004a) study is one of several studies of the effectiveness of different alarms to awaken different populations. A series of studies tested responsiveness to different alarm signals in sleeping children aged 6 to 10 years (Bruck, Reid, Kouzma and Ball, 2004). It was found that the children awoke to only 57% of the 89 dBA signal presentations of the high pitched smoke alarm. By contrast, arousal rates were 94% or more with the other 89 dBA signals, which were recordings of their mother's voice (saying their name about once every six seconds), female actor's voice and the mixed T-3 alarm (all alarm signals were as in the study of alcohol impairment discussed above). All of the more effective signals had dominant tones below 2,500 Hz. The time taken for the children to wake up was also less with the latter three signals, with all awakenings within 60 seconds. In contrast, nearly a third of the children who woke up with the high pitched signal required longer than 60 seconds.

A study of 45 older adults (aged 65 to 83 years) also found that the mixed T-3 signal performed significantly better than a high pitched T-3 signal (3100 Hz), with the median auditory arousal thresholds of each differing by 20 dBA (Bruck, Thomas and Kritikos, 2006; Bruck and Thomas 2007a). The mixed T-3 signal also awoke participants at lower volumes than a 500 Hz pure tone T-3 signal and a male voice alarm. In this study sleep stage was controlled and awakenings were from stage 3 sleep (one of the deeper stages of sleep).

Taken together the different studies have consistently shown that the mixed T-3 is a more effective signal than a high pitched pure signal for waking different types of sleepers under controlled conditions.

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 sound pressure level 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 alarms 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 & Laroche, 2003). The signal emitted by most current smoke alarms is around 3,000 Hz or more (Lee, 2005).

2.3 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 the hearing impaired and deaf) 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.[3] Three studies report responsiveness during sleep to a vibrating 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 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 these 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%

[3] A comparison of different shakers is contained in the companion report "Waking effectiveness of alarms (auditory, visual and tactile) for the hearing impaired" by Bruck and Thomas (2007b).

from SWS), however, awakenings were often slower in this group, with 19% requiring more than a minute to wake up.

3. Du Bois, Ashley, Klassen and Roby (2005) found that a continuous bed shaker (which we understand was placed under the mattress) was differentially effective with different populations; 92% effective for the hearing able (n=34), 82% for those with partial hearing (n=45) and 93% for the deaf (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 13/8 inches and notes a frequency of 100 Hz.4 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 the deaf or hard of hearing incorporates an auditory smoke alarm as well a combination of a vibration pad 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

[4] This is different to the two shakers purchased in the US and sent to the authors, which were similar to the bed and pillow shakers, purchased in Australia and used in the current study.

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. 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 as an option for the emergency awakening of hearing impaired people. However, the literature is quite variable 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) 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, 1Hz 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, averaged across three different stages of sleep. Overall, a trend for decreased awakenings with strobes from deep sleep was noted but percentages were not reported. Details of the strobe's placement and 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 the 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 assessed 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). 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

The overall aim of this study was to investigate the effectiveness of auditory, visual and tactile signals for their ability to alert the moderately alcohol impaired (.05 Blood Alcohol Content, BAC) in residential settings. Because of the large variability in people's ability to wake up arising from both individual differences and sleep stages (Zepelin, McDonald and Zammit, 1984) the study was designed such that each participant was exposed to a variety of different signals and always awoken from the same type of sleep, which was the deepest stage of sleep, stage 4.

The research questions that were addressed are as follows:

1. Are different auditory signals differentially effective in waking alcohol impaired young adults in deep sleep under the testing conditions? The following auditory signals were tested:
   - 400 Hz square wave signal in T-3 pulse
   - 520 Hz square wave signal in T-3 pulse
   - 500 Hz pure tone in T-3 pulse
   - 3100 Hz pure tone in T-3 pulse (as in the current smoke alarm)
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 T-3 pattern?
3. Do strobe lights provide an effective means of waking up from deep sleep for the alcohol impaired? Is the NFPA 72 standard for the intensity of strobe lights (177/110 cd) high enough to effectively awaken this population under the testing conditions (using a modified T-3 pattern), or are strobes of a higher intensity required for awakening?
4. How do each of the signals perform with the alcohol impaired population in comparison to the applicable standard, or in the case of the tactile devices, to the intensity level as purchased?
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 alcohol impaired?

6. How do the auditory signals, shakers and strobe lights compare in terms of waking effectiveness?
7. 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?
8. To what extent do sex differences in arousal thresholds exist across a variety of signals?
9. Are there differences across the different signals in the time taken between EEG wakefulness and responding behaviourally as instructed (pressing a button)?

In sum, the signals to be tested are as follows:

Signals
400 Hz square wave signal in T-3 pulse
520 Hz square wave signal in T-3 pulse
500 Hz pure tone in T-3 pulse
3100 Hz pure tone in T-3 pulse
Bed shaker- under mattress – T-3 pulse
Pillow shaker – T-3 pulse
Strobe light- T-3 pulse (modified)

The spectral analyses of the auditory signals are presented in Appendix A. The 520 Hz fundamental frequency of the second signal listed was chosen as this was equivalent to the fundamental frequency of the “mixed T-3’ reported in previous studies (Ball and Bruck, 2004a, 2004b; Bruck et al, 2004; Bruck, Thomas and Kritikos, 2006).

The study was designed so that each participant received six signals over two nights. As described above a total of seven signals were investigated. Two thirds of the way through data collection the pillow shaker was replaced by the 3100 Hz pure tone. As far as possible all participants received presentations of all the other five signals.

The research was conducted on young adults, aged from 18 to 26 years, for several reasons.

- Sleep patterns change with age, so variability in the data is reduced by restricting the population to a narrower age range.

- Young adults as a group are the deepest sleepers of all adult aged populations (Zepelin et al. 1984), so they form a useful model for documenting arousal thresholds, with group results likely to yield the highest thresholds across all adult age groups.
- This age group is known have a greater quantity of deep sleep per night than older adults, maximising the number of awakenings in Stage 4 sleep that could consistently be achieved.
- Many young adults have a lifestyle which includes social alcohol drinking prior to sleep, so testing with this group has considerable ecological validity.
- This age group was convenient to recruit, as university classes could be used to disseminate information when seeking volunteers.

A signal presentation duration of thirty seconds of each intensity level, followed by silence, was chosen as the available literature suggests that if a participant is going to wake to a particular intensity of a signal it will usually be within 30 seconds. Du Bois et al. (2005) noted that 88% of the time when participants awoke, they did so within 30 seconds of the signal being activated. Similarly, Bruck et al. (2004) found that, of the children who awoke to a signal, 67-79% did so within 30 seconds of the sound starting, depending on the nature of the sound.

In this study a pulsating signal was used 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.

4 Method

4.1 Participants

Participants for the current study were recruited from the student body of Victoria University, their friends and family. Data was collected from 32 participants (15 male, 17 female) aged from 18 to 26 years (mean = 21.2, SD = 2.6). Four participants withdrew after one night of data collection. People were recruited who met the following criteria:

- Be self reported "regular drinkers" of alcohol; i.e. they consumed alcohol at least one night per week. This criterion was designed according to the Australian National Drug Strategy (1998).
- Passed the hearing screening test. All participants had auditory thresholds of below 20 dBA for all tones. Tones at 500, 1000, 2000 and 4000 Hz were tested.
- Report that they do not regularly take medication that affects their sleep,[5] 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 have affected their ability to perceive or respond to a visual, tactile or auditory signal
- Be aged between 18 and 26 years.
- Give informed consent.

Recruitment of participants was conducted through flyers distributed around two University campuses, promotional talks at the end of lectures and word of mouth advertising. All participants were recruited for a three night study, of which the first two would be with .05 BAC and the final night would be sober.[6] Compensation for inconvenience was $80 AUS per night with a $75 completion bonus to be paid after all three nights were completed. The Information Sheet informing potential participants about the study is contained in Appendix B.

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

[6] The research results of the sober night (with auditory signals only) is beyond the scope of the current research but will be reported separately later during 2007.

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).

Sleep recording and environment: Polysomnographic recordings were conducted using the Compumedics Siesta wireless data acquisition system or Compumedics Series E data acquisition system. The sleep 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 C.

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. Seven participants chose to undergo their testing in the Sleep Laboratory. For each person all nights of testing were conducted in the same environment. Signal delivery equipment for sounds, shakers and lights was set up each night, to reduce any expectation effect. 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 particpants completed the questionaire asking for a self report on such issues (see Appendix D).

Signal delivery: 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 this study four auditory signals were evaluated during sleep and presented initially at 55 dBA increasing in 10 dBA increments until 95 dBA (the nature of the sounds was described in Section 3). All sounds except the 3100 Hz pure tone were created on the computer. The 3100 Hz signal was from a recording of a smoke alarm.[7] The spectral profiles of all sounds as assessed in a typical bedroom are contained in Appendix A. 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. 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 Bellman and Smyfon AB of Sweden “Visit” bed shaker (recommended for placement under the pillow) and the bed shaker was adapted from the Vibralarm VSS12 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 consistent with the recommended placement discussed within the local deaf community. Photos of the bed and pillow shaker can be found in Appendix E. 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 set as level 3, and for other intensities 1 was the lowest level and 5 was the highest.[8] Pilot testing of tactile devices on the market showed that those with a pulse vibration alternated with a minimum of about one

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

[8] Full procedural details of the intensity testing of the tactile devices are presented in the companion report on adults who are hard of hearing (Bruck and Thomas, 2007b).

second on and one second off. Both tactile devices were modified to be in a T-3 pulsing pattern. The different intensities of the tactile devices are given in Table 4.2 (section 4.4 below). See Appendix E for photos of the two tactile devices. A questionnaire was completed by each ST documenting bed and pillow information (see Appendix F).

Strobe Light: The strobe lights[9] were presented to sleeping individuals at three levels of intensity, 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. In addition, a single strobe (i.e. the weakest intensity tested, level A) was stronger at the pillow than commercially available strobes. It was found that level A was 177 cd, level B was 210 cd and C was 420 cd.[10] 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. The temporal pattern is shown in Figure 4.1

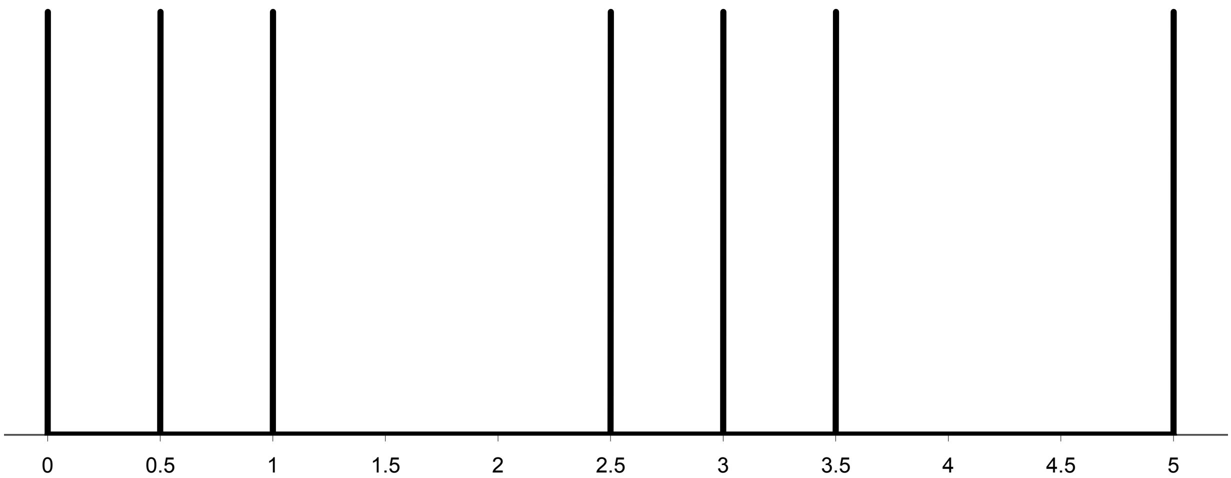

Figure 4.1: Flash pattern of the strobe lights as a function of time in seconds (cycle of three is repeatedly ongoing)

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

[10] Full procedural details of the intensity testing of the strobe lights are presented in the companion report on adults who are hard of hearing (Bruck and Thomas, 2007b). In addition, comparisons of the strobes used in this study with commercially available similar products from the US are also documented.

The strobe made a small clicking noise with each pulse. When one light was activated the volume was measured to be 41 dBA, with 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 G for instructions given to the Sleep Technicians for setting up the strobe light and Appendix E for a photo of the three strobes when set up.

Alcohol: The alcohol used for the current study was vodka (Smirnoff, 37.5% alcohol volume). This was mixed with unsweetened reconstituted orange or cranberry juice, according to participant preference. Several Lion Alcometre S-D2 breathalysers were loaned to the study by the Victoria Police to measure blood alcohol content (BAC). For further details of these units please see Appendix H.

4.3 Procedure

After each volunteer had given informed consent a Project Officer performed the hearing screening test on a day prior to the sleep testing. Those who passed the hearing test were then assigned to a Sleep Technician (ST) who contacted them to arrange a mutually convenient time for the study to take place. During this contact the importance of avoiding alcohol on the day of testing and ensuring sufficient prior sleep was emphasized.

Data was collected by a team of paid STs. Every effort was made to match the sex of the ST to the participant. Six signals were tested across two nights (three signals per night). Signals were presented in a counterbalanced order with the exception that the final signal was to be auditory on one night, and tactile on the other.[11] 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

[11] In a companion report (Tokley, Ball, Bruck and Thomas 2007) sleep inertia upon waking to a tactile stimulus is compared to sleep inertia upon waking to an auditory stimulus. To achieve the assessment of sleep inertia a variety of cognitive tests were administered to the participants in the current study at various points in the procedure and all details related to this research are available in the separate report.

approximately two 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 may be awoken to something they would 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 C.

After the equipment was correctly set up and the sound level calibrated, the electrodes for polysomnographic recording were applied. Alcohol administration was also commenced while this occurred. Electrodes were attached according to the standard placement set down by Rechtschaffen & 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.

Participants were asked to abstain from drinking alcohol on the entire day of testing, with the exception of any alcohol provided by the researcher. Alcohol was administered in measured standard doses as laid out by the Australian Transport Safety Bureau. The operational definition of one standard dose used for the current study was 1 standard nip of vodka (30ml), mixed with equal parts of the participants' choice of juice as described above (60ml total). Multiple doses were often administered as one drink before a participant was breathalysed (for example, a single 180ml drink consisting of three doses).

Participants ingested the alcohol drink at their own pace. The initial number of standard doses administered to attain the desired BAC on any given night was estimated by the ST in consultation with the participant. Estimations were based upon factors that are known to affect the absorption of alcohol such as the participant's previous experience with alcohol, their sex, their weight, time since their last meal, etc. A conservative estimate was always made to minimise the possibility of overshooting the desired level. Breath testing was conducted ten minutes after the first alcoholic drink was completely consumed. (See Appendix H for BAC testing procedural details.)

After the required alcohol level was reached (.05 BAC + .01) participants were settled in bed and instructed on the procedure to follow when they became aware of the signals sounding. They were asked to press 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. They then completed a 10 minute series of cognitive tests, using a stable table while sitting up in bed. After completing the tests a BAC reading was again taken and this reading is reported in the results as the BAC prior to sleep. Lights were then extinguished.

After lights out the ST monitored the participant's EEG output until Stage 4 sleep was confirmed for a minimum of three consecutive 30 second epochs. Once stage 4 sleep 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.

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. 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 awaken 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 4.1 sets out the relevant temporal specifications of the delivery of the different signals and Table 4.2 gives the intensity measurements at each level for the auditory and tactile signals. Notice that all the auditory and tactile signals, except the strobe lights 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 commenced during stage 4 sleep but continued to be presented even if a 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 4.1: 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

There were two measures of awakening recorded;

1. EEG wake time, which was the exact time of awakening as determined by the scoring of the sleep recording. This was recorded as the total time (in seconds) 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.

If a participant failed to respond at all, awakening was recorded as taking 500 seconds (20 seconds longer than the actual total time from signal 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 4.2. 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 the 500 Hz pure sound 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 2.2). 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. While subjectively there was a substantial difference between the pillow shaker and bed shaker, the numerical differences shown in Table 4.2 were greater than expected. It seems possible that humans 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.

Table 4.2: Temporal and intensity details of auditory and tactile signal presentations and corresponding Waking Score.

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}	

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 seven possible signals, 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 two dependent variables. The data was sometimes bimodal, being grouped at the lower points and uppermost level (where participants slept through and were arbitrarily allocated a time of 500 seconds). Thus descriptive statistics, frequency analyses, percentages and non-parametric statistics were used with such variables. Where the data was normally distributed (as for the time difference between EEG wake time and behavioural response time) inferential statistics were used. Where the dependent variables were ordinal data (i.e. the Waking Score) non parametric tests were used; the Mann Whitney U Test was used for two group comparisons and the Kruskal-Wallis Test was used to compare across three or more variables. 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 $p<.05$.

5 Results

5.1 Waking Scores

Waking Scores (based on EEG wake criteria) 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 scale and benchmarks are described in Section 4.4 above.)

Table 5.1 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 two tactile signals and the strobe lights had the greatest proportion of people who were sleeping through while under the influence of alcohol. In contrast, no participants slept through the two auditory signals that were square wave sounds. The auditory sounds clearly performed the best in terms of waking participants at or below the benchmark. Given that all strobe levels were above the standard, they clearly performed the worst of all signals presented.

Table 5.1: Number and percentage of participants in terms of their waking behaviour to different signals with .05 BAC.

	Awoke at or below benchmark		***Awoke above benchmark***		***Slept through all levels***	
	Number	**%**	**Number**	**%**	**Number**	**%**
400 Hz square wave	26/28	93%	2/28	7%	0/28	0%
520 Hz square wave	27/27	100%	0/27	0%	0/27	0%
500 Hz pure tone	24/28	86%	3/28	10.5%	1/28	3.5%
3100 Hz pure tone	8/13	61.5%	4/13	30.8%	1/13	7.7%
Bed shaker	18/28	64.5%	3/28	10.5%	7/28	25%
Pillow shaker	11/19	58%	2/19	10.5%	6/19	31.5%
	Awoke at level A		***Awoke at level B or C***		***Slept through***	
Strobe light*	6/25	24%	11/25	44%	8/25	32%

*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 5.2. The mean values shown reinforce the data presented in Table 5.1, showing the greater effectiveness of the two squares in waking participants at lower intensity levels.

Table 5.2: 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	2.0 (1.6)	1	55 dBA	1-7
520 Hz square wave	2.3 (1.3)	3	65 dBA	1-5
500 Hz pure tone	3.6 (3.3)	3	65 dBA	1-12
3100 Hz pure tone	4.9 (3.3)	3	65 dBA	1-12
Bed shaker	5.0 (4.6)	3		1-12
Pillow shaker	5.5 (5.2)	3		1-12
Strobe light*	8.6 (2.9)	7		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 four auditory sounds a Kruskall-Wallis test was performed using the Waking Score as the dependent variable and a significant difference was found (χ^2=9.04, df=3, p=. 03).[12] The pattern of results suggests that the two square wave sounds were significantly more effective at low intensity levels than the two pure sounds. 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*=305, p=.91).

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.

[12] A further analysis of just the 13 participants who completed the 3100 Hz sound and the two square wave sounds also found a significant difference (Friedman test χ^2 = 15.32, df=2,p=.000).

The graphs illustrate the lower Waking Scores achieved by more participants with the two square wave auditory signals compared to the other signals.

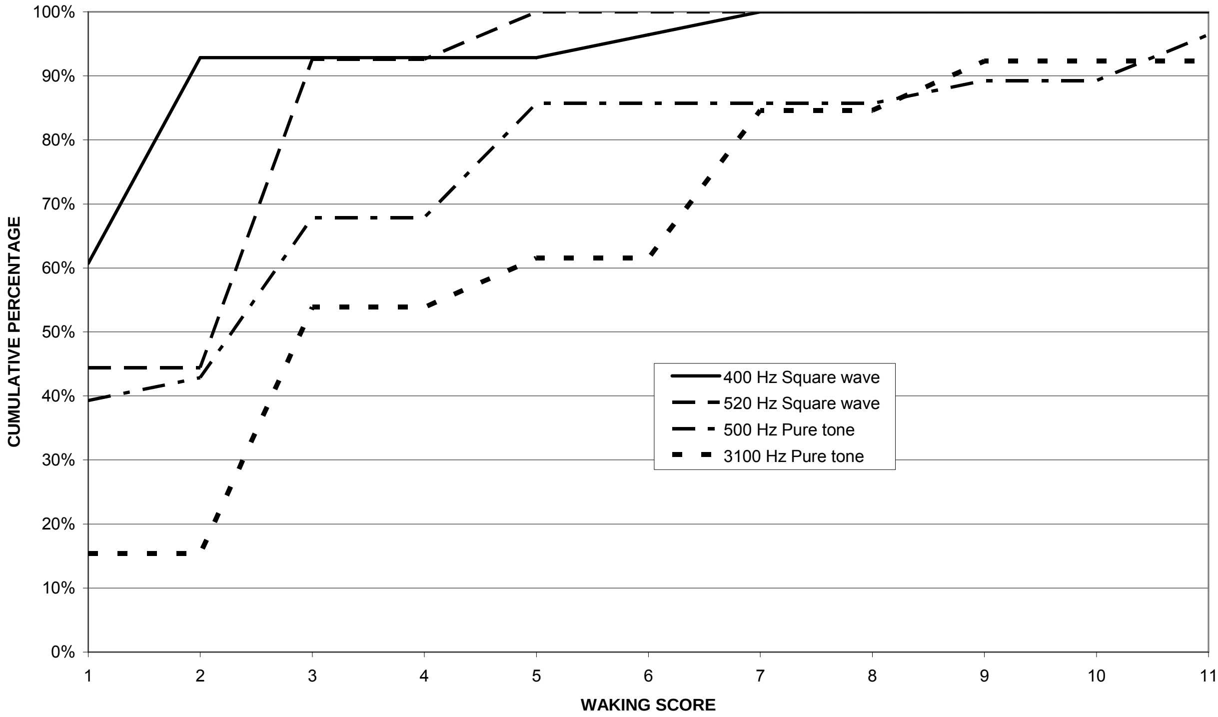

Figure 5.1: Cumulative frequency graphs for Waking Scores for the four auditory sounds.

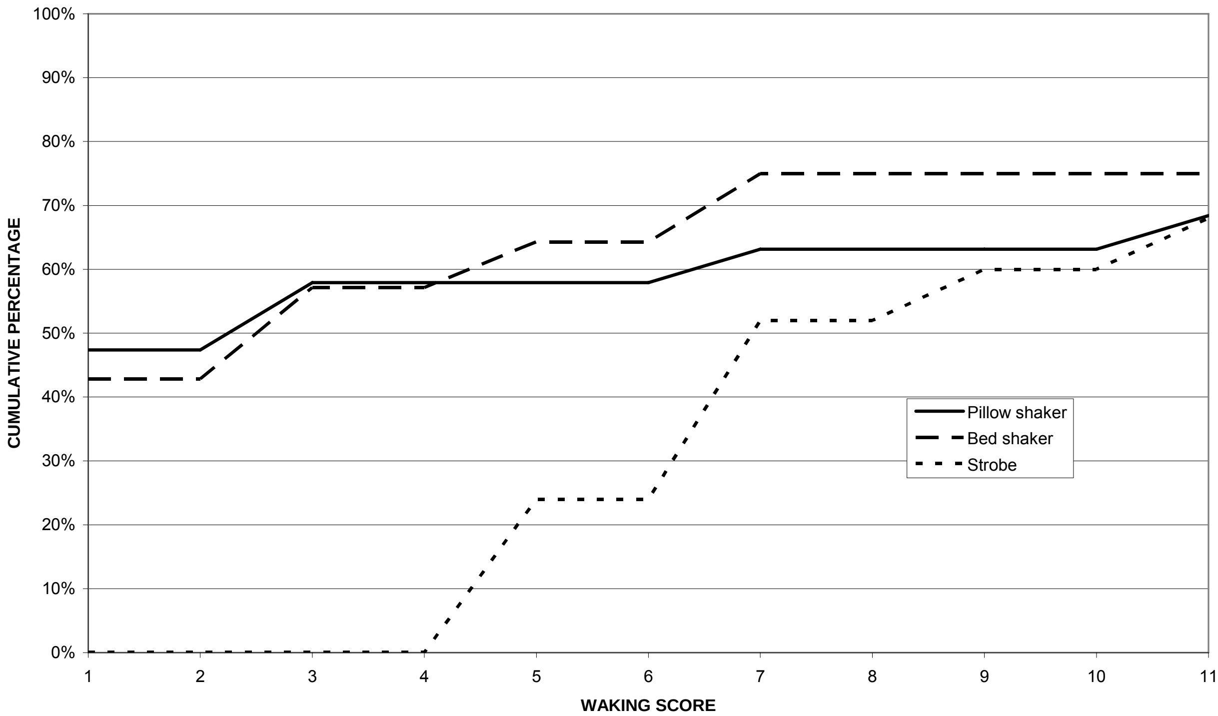

Figure 5.2: Cumulative frequency graphs for Waking Scores for the two tactile signals and strobe lights. (Note that for the strobe lights Waking Scores commenced from level 5.)

5.2 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 rest of the no signal pause (with this being for 30 seconds for all signals except the strobe where the pause was for 70 seconds)

Figure 5.4 presents the percentage with which each type of awakening occurred and shows that very few awakenings occurred during the signal offset periods. It also shows that overall most awakenings were within 10 seconds of signal onset but this varied across different signals. The signal that was most effective in awakening participants shortly after it started was 520 Hz square wave. In considering Figure 5.4 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.

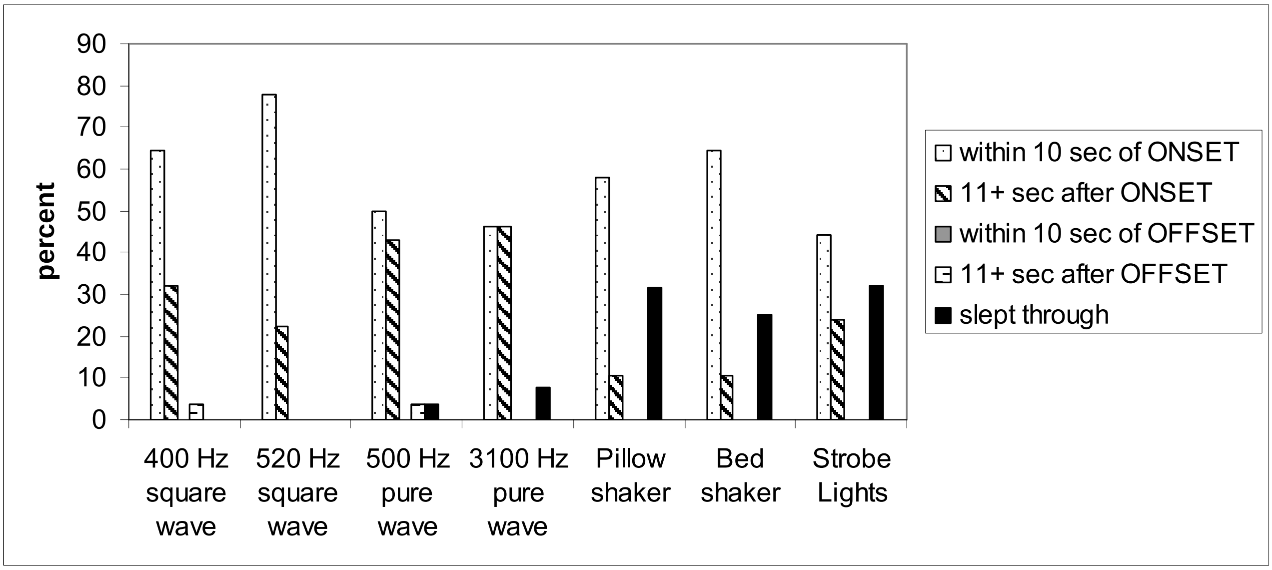

Figure 5.4: Percentage of awakenings as a function of timing of the onset and offset of each signal.

5.3 Sex differences

The possibility of sex differences in the waking effectiveness of different signals under .05 BAC alcohol levels 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 5.3. No significant sex differences or trends were found for any of the signals.

Table 5.3: The means, standard deviation and statistical results 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	2.2 (1.7)	1.9 (1.4)	85.0	.58
520 Hz square wave	2.4 (1.2)	2.1 (1.3)	76.0	.48
500 Hz pure tone	3.3 (2.3)	3.9 (4.0)	91.0	.89
3100 Hz pure tone	5.7 (2.3)	4.7 (3.6)	11.0	.57
Bed shaker	5.4 (4.6)	4.5 (4.6)	79.5	.41
Pillow shaker	5.4 (5.0)	5.7 (5.9)	41.5	.96
Strobe light*	8.8 (2.6)	8.4 (3.2)	73.5	.81

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

5.4 Behavioural Response Time

Table 5.4 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 sec was assigned. For this reason it may be more instructive to consider the median behavioural response times. It can be seen that, again, the two square wave signals produced the fastest behavioural response times and the 3100 Hz pure tone and the strobe lights had the slowest behavioural response times. The Kruskal-Wallis test comparing the four auditory sounds found a highly significant difference (χ^2=15.3, df=3, p=. 002), while a Mann Whitney U test found no significant difference between the two tactile signals (*U*=205, p=.92).

Table 5.4: Descriptive statistics for behavioural response time (in seconds) across the different signals.

	Mean (standard deviation)	***Median***	***Range***
400 Hz square wave	60.6 (62.1)	31.5	11 - 247
520 Hz square wave	57.7 (47.1)	66.0	4 - 150
500 Hz pure tone	117.5 (113.5)	86.0	16 - 500
3100 Hz pure tone	157.2 (123.5)	132.0	18 - 500
Bed shaker	185.9 (202.0)	89.0	5 - 500
Pillow shaker	214.6 (223.8)	80.0	5 - 500
Strobe light*	244.1 (201.9)	174.0	6 - 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).

The difference 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). The descriptive data for this time difference is summarised in Table 5.6 as a function of the different signals.

Table 5.5: Mean differences between behavioural response and EEG awake times

	Mean (standard deviation)	***Median***	***Range***
400 Hz square wave	8.7 (10.4)	6.5	1 – 51
520 Hz square wave	14.3 (22.5)	5.5	1 – 84
500 Hz pure tone	22.3 (38.1)	9.0	1 - 175
3100 Hz pure tone	17.7 (27.8)	5.0	1 – 70
Bed Shaker	11.9 (28.6)	5.0	1 – 136
Pillow Shaker	18.8 (28.1)	6.0	3 – 86
Strobe	9.0 (23.5)	3.0	1 – 107

A one way ANOVA was performed across all seven signals for the time difference between EEG wakefulness and behavioural response time (mean values as in Table 5.5) and no significant difference was found between the signals (F=0.82, df = 6,134, p=..56). 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.

5.5 Blood Alcohol Content

In the experimental procedure alcohol was consumed until a .05 BAC level was measured (.06 BAC was also acceptable). After this level was obtained the participants all undertook a 10 minute block of cognitive performance tasks and then went to bed. The "prior to sleep' value in Table 5.6 is the value taken AFTER the cognitive tests and immediately prior to lights out. It can be seen that in most cases the BAC prior to sleep was at the target level of .05 BAC. As the aim was for participants to be on the rising BAC curve at sleep onset it is unsurprising that a quarter were at .06 BAC prior to sleep. After the final signal was delivered and the subject was awake the BAC was again measured and Table 5.6 shows that the range varied considerably, with most participants being from .03 to .05 BAC. The careful counterbalancing of the presentation order of signals means the differential effect of different BAC levels across the time course of the participant's sleep was minimal (see also next section).

Table 5.6: Percentages of participants at different blood alcohol content (BAC) levels at two time points.

	% at BAC level prior to sleep	*% at BAC level after final awakening*
.01 BAC		4.8%
.02 BAC		9.5%
.03 BAC		23.8%
.04 BAC	8.3%	33.3%
.05 BAC	62.5%	28.6%
.06 BAC	25.0%	
.07 BAC	4.2%	

5.6 Order of signal presentation effects

An analysis was completed to determine whether there were any significant effects that were a consequence of the order in which the signals were presented. That is, whether it was the first, second or third signal on any one night. It was especially important to examine whether this was a confounding variable as BAC reduced across the night. A one way ANOVA found no such confounding order effect ($F=1.01$, $df=2$, $p=.37$).

6 Discussion

6.1 Waking effectiveness of different signals

Auditory signals: In comparing the waking effectiveness across the four auditory signals presented it can be seen that the two low frequency square waves (with 400 Hz and 520 Hz fundamental frequencies) performed significantly better than the low frequency (500 Hz) pure tone and the high frequency (3100 Hz) pure tone (as in the current smoke alarms). The direction of the findings are quite clear and consistent across the different variables examined and the different analyses undertaken.

These analyses showed that:

- With the two square wave signals 93%-100% awoke at or below the 75 dBA benchmark compared to 61.5%-86% with the two pure tones.
- No participants slept through the square waves at 95 dBA, while 3.5%-7.7% slept through the 95dBA pure tones.
- A significant difference was found across the four auditory signals when the ordinal variable, Waking Score, was used. The mean and median values clearly show that the two square waves were the most effective waking signals.
- The square wave signals lead to more prompt EEG awakenings (i.e. within 10 seconds of signal onset) than the pure tones.
- Behavioural response time (i.e. time from signal onset at the lowest intensity to pressing the bedside button) was faster with the square waves than with the pure waves.
- The results for the two square wave signals (400 Hz and 520 Hz) show they were approximately equivalent in terms of effectiveness.
- The results for the two pure tones (500 Hz and 3100 Hz) show that the 3100 Hz signal was somewhat less effective at waking participants promptly than the low frequency pure tone.

The finding that the 400 and 520 Hz square wave signals were more effective at waking alcohol impaired participants than a high pitched pure wave is consistent with the findings of Ball and Bruck (2004a). They showed that a 520 Hz square wave[13] aroused .05 BAC and .08 BAC young adults significantly more effectively than a 4000-5000 Hz pure tone. The current results are also consistent with the Bruck et al. (2006) research involving 45 participants aged 65-83 year. They found that 16% to 18% slept through the two pure tones presented (500 Hz and 3100 Hz respectively), while only 5% slept through the 520 Hz square wave. In that study the differences between the 3100 Hz pure tone and the 520 Hz square wave were statistically significant, with a trend for differences between the 500 Hz pure tone versus 520 Hz square wave comparisons.

Thus the evidence suggests that the inclusion of the harmonics (3rd, 5th etc) in the square wave of a low frequency tone is important in helping people wake up at lower volumes. Further, it is clear that there were no important differences in the responsiveness of participants in the current study to a 400 Hz or 520 Hz square wave signal. It needs to be determined if other mixed frequency signals, with perhaps higher dominant frequencies and/or higher harmonics, are equally or more effective at waking people up.

It is not immediately obvious why the square wave signal should be the most effective signal 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 2004a). 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,

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[13] Called the “mixed T-3”.

> 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 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 A).

Given the above research, the results of the current study using moderately alcohol impaired sleepers 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 un-primed home situation it is likely that only some signals 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) and previous experience with smoke alarms and/or fire situations.

We are currently undertaking studies comparing signals with a range of pitches and patterns (including white noise and whooping sounds covering a range of frequencies) to determine their differential effectiveness in waking sober and unimpaired young adults. Ideally the best sounds should also be tested in large numbers of un-primed sleepers in their own home environment.

<u>*Pillow and Bed shakers:*</u> The results show that, under the testing conditions, 32% slept through all levels for the pillow shaker and 25% slept through with the bed shaker. If we consider how many .05 BAC young adults slept through the shakers that are at the "off the shelf" intensity level (i.e. when purchased), the results show that for the pillow shakers 58% slept through and for the bed shakers 65%. These results suggest bed and pillow shakers are much less effective with these alcohol impaired individuals than has been previously reported in sober adults (with variable hearing abilities), where successful awakening rates ranged from 70% to 100% (Underwriters Laboratory, 1991; Murphy et al, 1995; Du Bois et al. 2005). The results in the DuBois study were reported as a composite across several sleep stages and 100% awakening with the intermittent bed shaker was reported in both hearing impaired and normal hearing adults (across all adult age ranges). It is hard to ascertain to what extent the differences across all the bed shaker studies are due to the different devices used, different placement of the bed shakers, sleep depth differences (which will vary across the night as well as with different adult ages), unknown individual differences or the sober versus alcohol impaired conditions. The conclusion from the current study is that the two tactile devices are not effective for waking moderately alcohol impaired participants, either at the off the shelf intensity level of the bed and pillow shakers used, or at higher intensities.

<u>*Strobe Lights*</u>: 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 24% awoke to the lowest intensity level. Thus the results show that under the te4sting conditions at least three-

quarters of .05 BAC young 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 less than a third of their sober normal hearing participants awoke to a strobe which was less intense than the lowest intensity level in the present study. It is 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 still 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 alcohol impaired participants.

Comparison across all signals: The results clearly show that both the 400 Hz and 520 Hz square wave auditory signals were more effective at awakening young adults intoxicated at .05 BAC level than the 500 Hz and 3100 Hz pure tones, bed shakers, pillow shakers or strobe lights. The bed and pillow shakers were about equivalent in terms of effectiveness and all signals performed better than the strobe lights, even though for the strobe lights the lowest intensity presented was above the level required in the standard.

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. 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. From the current results it is clear that the 1.5 second gap in the T-3 signal is too short to prevent sensory adaptation from occurring while asleep, so a T-3 signal sounding continuously is perceived as a continuous signal.

Interestingly, in the current study the mean decibel levels at which participants awoke were about 15 decibels lower than in the study by Ball and Bruck (2004a) testing 0.05 BAC young adults. There are two possible reasons for this. Firstly, in the earlier study participants were recruited on the basis that they were self-reported deep sleepers, whereas this was not the case in the current study. Secondly, in the 2004 study each level of a signal was presented sequentially, without any intervening period of silence. It is possible the signal sounding after a period of silence makes it more likely to awaken a sleeper compared to when the signal had already been on, with some sensory adaptation having occurred. It is probably more ecologically valid to test a signal cutting in from silence; however, the presentations without silences would still enable valid conclusions to be drawn about the *comparative* efficacy of different signals.

6.3 Sex 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. This is consistent with the inferential statistic (mixed anova) results across male and female sober, .05 BAC and 0.08 BAC young adults for auditory sounds in Ball and Bruck (2004a). It is inconsistent with the conclusion from the application of stochastic modelling to that data which suggested that females responded faster than males at all alcohol levels 0.05 and 0.08 BAC (Hasofer, et al. 2005).

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. This variable could be considered to be a simple measure of sleep inertia. What was of particular interest from this data was the large individual variability which was not the result of just a few individuals having consistently more sleep inertia for all signals. Almost all the signals had maximum response delays of over a minute. It will be interesting to compare this data with the response delays when the participants are sober.

6.5 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 alcohol impaired people there are several considerations. The factors that would make it likely that *more* people would awaken in the field compared to in this study are as follows:

- This research has used young adults, which are known to have the highest arousal thresholds across all adult age groups (Zepelin et al, 1984). Older adults may awaken more easily.
- This study has attempted to awaken people from their deepest stage of sleep. Slow wave sleep (stages 3 and 4) occupies less than a quarter of normal adult sleep across the night (with the proportion decreasing with age). However, deep sleep predominates in the early part of the night when most fire fatalities occur.

The factors that would make it *less* likely that people would awaken in the field compared to in this study are:

- All research participants were expecting to be exposed to various signals to see if this would awaken them. Previous work has shown that such an expectation, which increases signal meaningfulness, increases the likelihood of waking up (Wilson and Zung, 1966; Oswald, Taylor and Triesman 1960).
- In this study only a *moderate* level of alcohol intoxication was induced. To obtain a BAC of .05 typically only 2 - 4 standard drinks are required, although this does vary with a variety of factors such as the participant’s previous experience with alcohol, their sex, their weight, and time since their last meal. In the field BAC levels may often be higher and thus responsiveness during sleep will be further reduced (Ball and Bruck 2004a). Interestingly, in studies of alcohol blood concentrations in fire victims (via coroners’ reports), the levels are more than .1 BAC (Brennan and Thomas 2001, Watts-Hampton 2006).

The differential effect of these factors mean that any extrapolations of absolute values (e.g. sound levels, intensities and percentages responding to signals) 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, comparative conclusions as to efficacy can be expected to be valid.

It is possible that as alcohol has a sedating effect (after an initial stimulating effect), its influence on arousal thresholds may be similar to that found in people having consumed hypnotic medication (sleeping tablets), especially during the first half of the night. Both inter-subject and intra-subject designs suggest that thresholds to a pure tone can be approximately 30 dBA higher when a hypnotic drug is exerting its maximum effects (120-150 minutes post-ingestion) than after ingesting a placebo. Arousal thresholds returned to normal three hours after ingestion (Johnson and Spinweber, 1984) Fifty percent of those receiving a hypnotic (triazolam) failed to respond to three 60 second 78 dBA smoke alarms when they were presented during deep sleep about two hours after drug intake alarm. This compared to 100% arousal from those taking the placebo (Johnson, Spinweber, Webb and Muzet, 1987). It is quite possible that the best signal for emergency awakening when under the influence of one type of chemical impairment (e.g. hypnotics) is the same as for a different type of chemical impairment (e.g. alcohol). While comparisons of the level of the sedating effects across chemicals will always be dependent on the specific doses, types of chemical ingested and individual variability, there may be validity in generalizing results about the best alerting signal found with alcohol impairment to hypnotic impairment. Given the large numbers of adults who ingest hypnotics on a regular basis, research on this specific issue would be valuable.

6.6 Conclusions and Recommendations

The main conclusions from this study are:

1. Some auditory signals are an effective means of waking moderately alcohol impaired (.05 BAC) young adults from deep sleep. Two signals, the 400 Hz and

520 Hz square wave T-3 sounds, were significantly more effective than the 3100 Hz pure wave T-3 sound.

2. Under the testing conditions a sound level of 75 dBA at the pillow was sufficient to awaken this population using either of the two square wave sounds. These signals awoke 93-100% of participants at 75 dBA or less. In contrast, the 3100 Hz signal awoke only 61.5% of the moderately alcohol impaired participants.

3. The bed shaker and pillow shaker devices tested were not an effective means of waking moderately alcohol impaired young adults from deep sleep, either at the intensity level as purchased, or at higher intensity levels. Only 58%-64.5% awoke at the intensity level as purchased.

4. Strobe lights were not an effective means of waking this population, with only 24% waking to the lowest strobe light intensity, which was more intense than that required by the standard (NFPA 72, 2002).

5. The results in this study are likely to be overestimations of the proportion of moderately alcohol impaired young adults 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.

6. It was found that, where 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 signal that is alternatively on and off for this period of time will be more effective than a continuously sounding signal.

Recommendations:

1. That bed shakers, pillow shakers or strobe lights, presented alone, should *not* be considered as an alternative emergency alarm for people with normal hearing.

   This recommendation is made on the basis that across the population a proportion of people sleep after having consumed alcohol, and visual and tactile signals will be less likely to awaken them than auditory signals. Furthermore, it is possible the findings with alcohol can be generalised to other types of sedating chemicals (e.g. hypnotic medication).

2. That further research be conducted to determine the nature of the best auditory signal (both in terms of spectral characteristics and on/off timing) to replace the current high pitch alarm.

   A square wave sound with a fundamental frequency in the lower ranges (i.e. 520 Hz) has now been consistently documented to be more effective than the current high pitched smoke alarm signal across a range of populations (children, older adults, sober young adults and alcohol impaired young adults). A signal that has an ON-OFF sound pattern of about 10-15 seconds may be more effective than a continuous signal.

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

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

Appendix A: Spectral analyses of auditory signals used.

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.

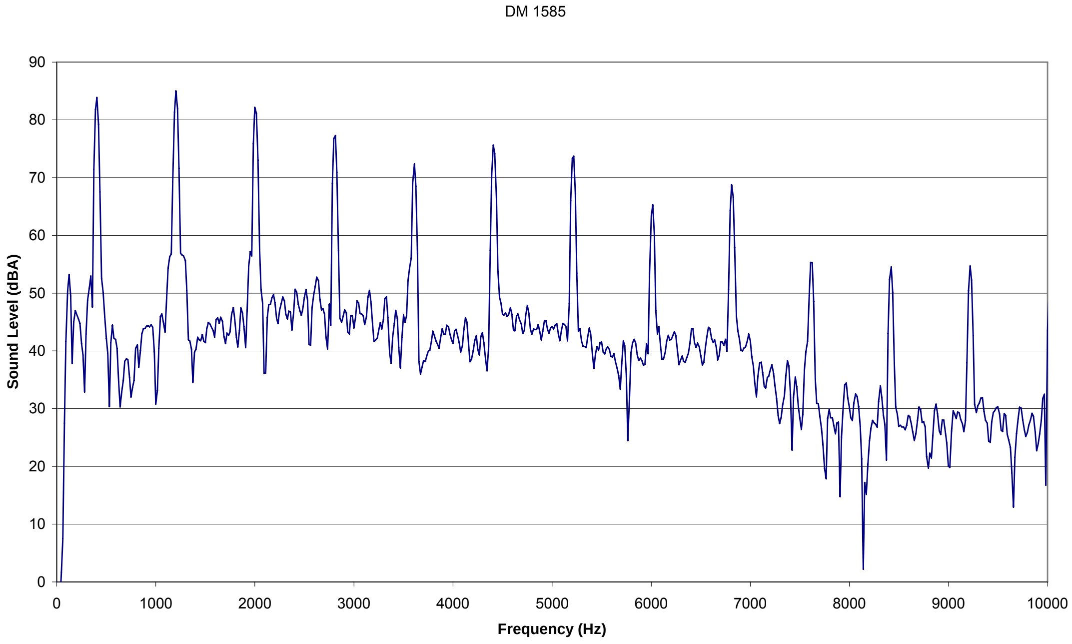


Figure A.1: Spectral analysis of the 85 dBA 400 Hz square wave in the testing bedroom. The fundamental frequency was found to be approximately 402 Hz.

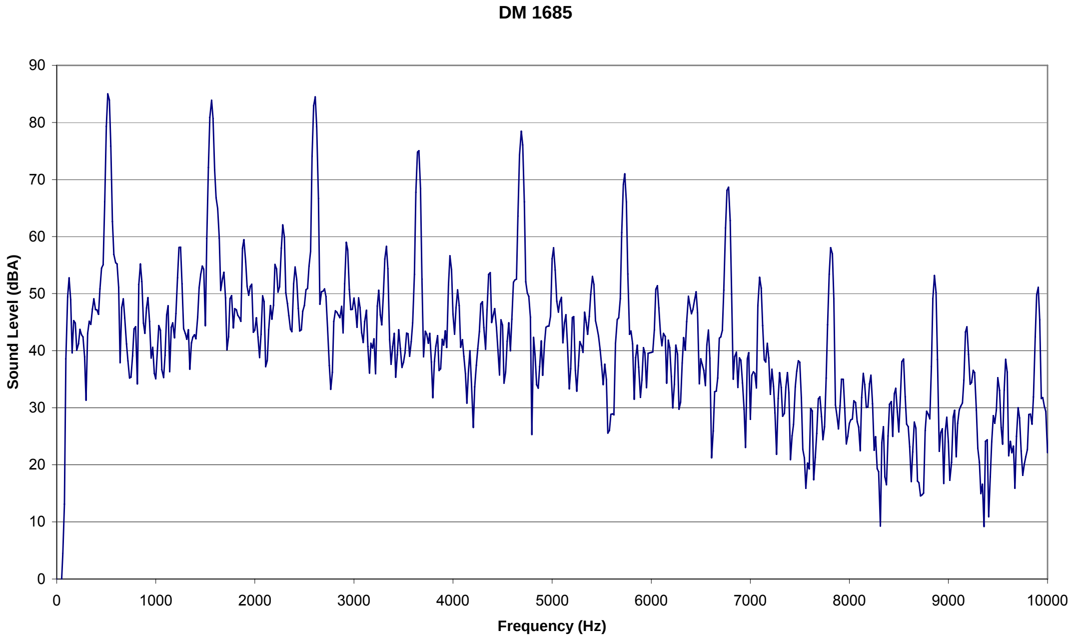


Figure A.2: Spectral analysis of the 85 dBA 520 Hz square wave in the testing bedroom. The fundamental frequency was found to be approximately 516 Hz.

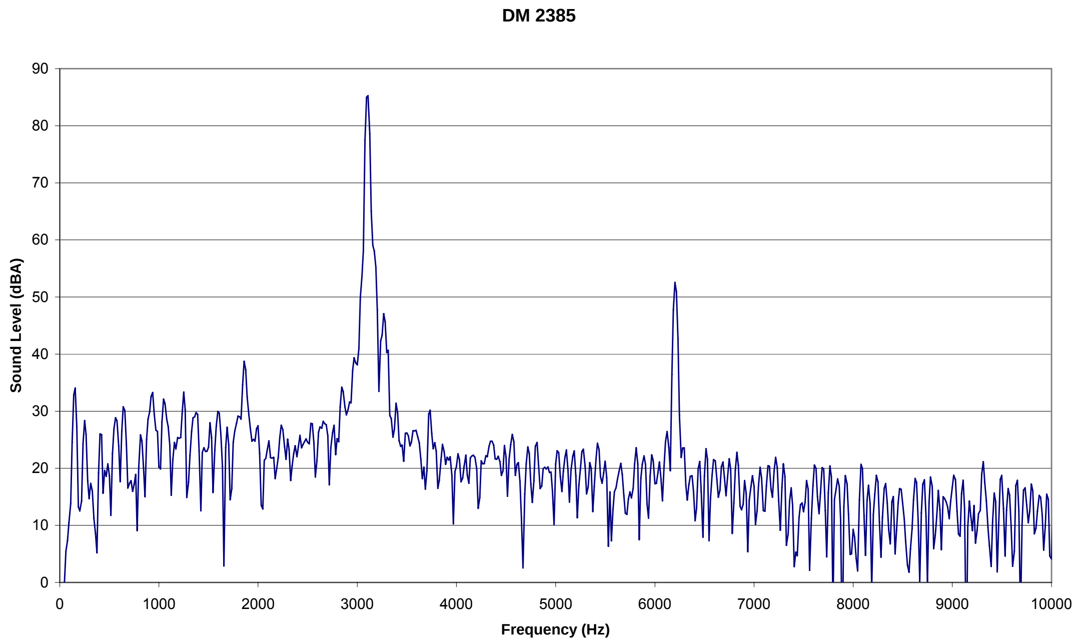


Figure A.3: Spectral analysis of the 85 dBA 3100 Hz pure tone in the testing bedroom. The fundamental frequency was found to be approximately 3110 Hz.

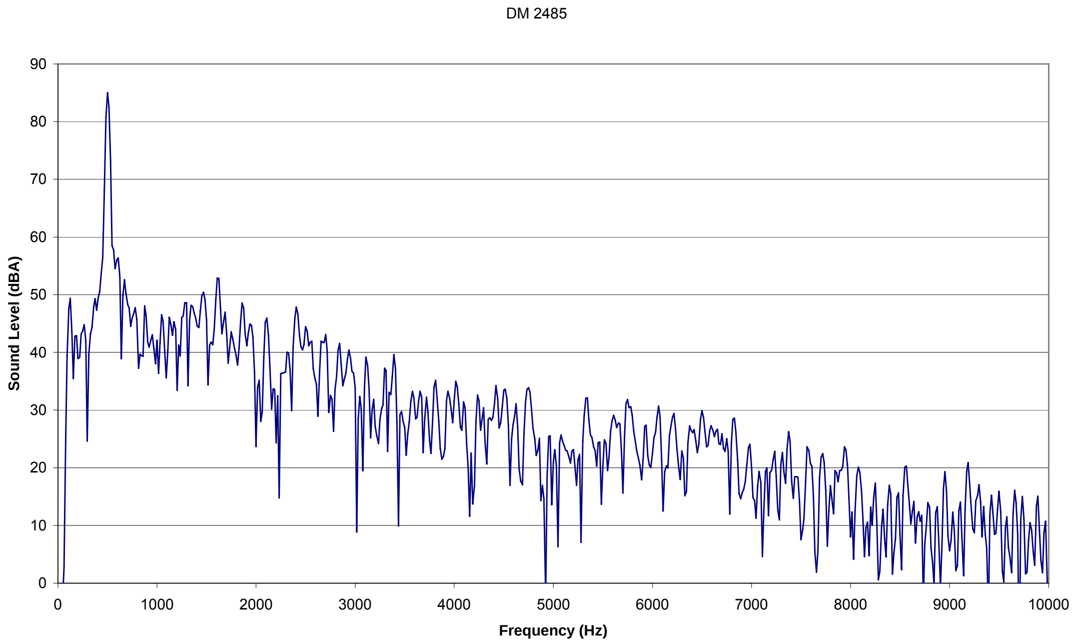


Figure A.4: Spectral analysis of the 85 dBA 500 Hz pure tone in the testing bedroom. The fundamental frequency was found to be approximately 500 Hz.

Appendix B: Information about the research project

<u>Title: Optimising fire alarm notification for individuals under the influence of alcohol</u>

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. Our most recent study was conducted with young adults and systematically varied the pitch and the pattern of signals in order to try and find the best possible alarm signal based upon what we now know. This process is ongoing, and we would now like to investigate different types of signals including lights or pads placed under the mattress or pillow that shake when there is a fire. We also need to test the best new signals drawn from the pitch and pattern study with people under the influence of alcohol, because drinking alcohol is the single most significant risk factor for death in a fire.

In this study 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. Usually 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 three nights, with at least three nights between each individual study night to prevent volunteers being affected too much by sleep deprivation. On the first two nights volunteers will be provided with enough alcohol to obtain a blood alcohol content (BAC) of .05 in the form of vodka mixed with orange juice. Their BAC will be measured using a breathalyser obtained from Victoria Police for the study.

Each volunteer will receive a total of nine signals during their sleep, normally three each night, thus three 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 an additional night.

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. This is especially important after nights when alcohol is taken in which case volunteers will be asked to sign an undertaking that they will not drive their car for a period of eight hours after their final drink.

We are also asking all volunteers to moderate their consumption of alcohol immediately prior to a night's testing and on the evening 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.

We are also interested in the issue of how groggy people are when they first wake up when they are under the influence of alcohol, compared to when they are sober. To this end we will be asking volunteers to complete a series of pencil and paper tests that measure thinking skills that might be useful in response to a smoke alarm, such as focused attention and problem-solving. They will do these tests before and after they have alcohol on the first night before sleep. They will then be asked to do them again after they wake up for the last time on each of the three nights of testing. At this time we will also ask if they remember incorporating any signals into their dreams and if so, which signal.

Because we realise that being part 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 three nights we will also be paying a $75 bonus on completion of all three nights. Thus the total payment for participation will be $315. For this project we need volunteers who meet our selection criteria. These are:

1. **Aged from 18 to 26 years (inclusive).**
2. **Believe that they have a normal hearing and pass a hearing screening test for both ears.**
3. **Do not regularly take medication to help them sleep.**
4. **Do not take medication that may interact with alcohol.**
5. **Report that they do not have a sleep disorder and pass some simple questions exploring this.**
6. **Report that they do not normally have difficulty falling asleep.**
7. **Report that they usually drink alcohol at least one night per week.**

Because hearing levels are so important to this study all volunteers are asked to undertake a free hearing screening test. We will arrange this at a time and place that is convenient for you (most likely at a campus of VU).

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: XXXXXXXXXXXXXXXXXXX

Appendix C: 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 Sl-4001 (2) both recalibrated on 31/8/05, 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 C.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 four 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 D: Screening questionnaire re sleep deprivation and alcohol

Please complete this questionnaire prior 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 one 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 E: 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 F: Data record sheet for <u>pillow & bed shaker</u>: pillow & mattress type

Select one option; if 'Other" please briefly describe:

Participant No:
Sleep Tech:

<u>PILLOW</u>

1. **Number of pillows used:** ____________

2. **Placement of Pillow Shaker:**

Between mattress & pillow Between 2 pillows Other ______________________________

3. **Width of pillow:**

Thin Medium Thick

4. **Pillow filling:**

Dacron Down (feathers) Wool Foam Other ______________________

5. **Pillow type:**

Normal Therapeutic

<u>MATTRESS</u>

1. **Mattress type:**

Inner spring Foam Futon Other ______________________________

2. **Mattress placed on:**

Mattress base Bed base (slats) Floor Other ________________________

3. Mattress thickness:

Thin Medium (normal) Thick

4. Mattress coverings:

Woolen underlay (Thick/Thin) Mattress protector Electric Blanket Other

OTHER COMMENTS:

****

The above form was designed to collect data on the types of bed and bedding used in the current study when the pillow and bed shaker were used. Given that the study was conducted in different bedrooms, it was thought that differences in the type and quality of materials may influence the effectiveness of these tactile devices. Qualitative data, for example pillow thickness, was based upon the subjective judgment of the sleep technicians. These factors were analysed for the first 27 participants.

Data was entered on the thickness of the pillow, and the placement of the device for the pillow shaker. Thickness of the pillow was coded as either Thin/Medium, or Thick. Pillow thickness was standard between participants, with only one person judged to be using a thick pillow, so comparison was not possible. For pillow placement, the data was coded as between the pillow and the mattress ($n = 12$), or between two pillows ($n = 7$). A t-test was performed and no significant differences were found, $t(16.9) = 1.907$, $p = .074$ (equal variances not assumed due to significant Levene's test).

For the bed shaker data was entered for mattress type and base type. Mattress type was coded as inner spring ($n = 21$), foam ($n = 1$), or futon ($n = 4$). Once again the disparity in group sizes meant that comparisons were not possible. Base type was coded as standard box mattress base ($n = 13$), wooden slats ($n = 11$), and floor ($n = 2$). Comparisons were made for standard mattress base and wooden slats. The t-test results showed no significant differences $t(21) = .573$, $p = .573$.

Appendix G: Strobe alignment and measurements - only required when strobe light signal is to be presented

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

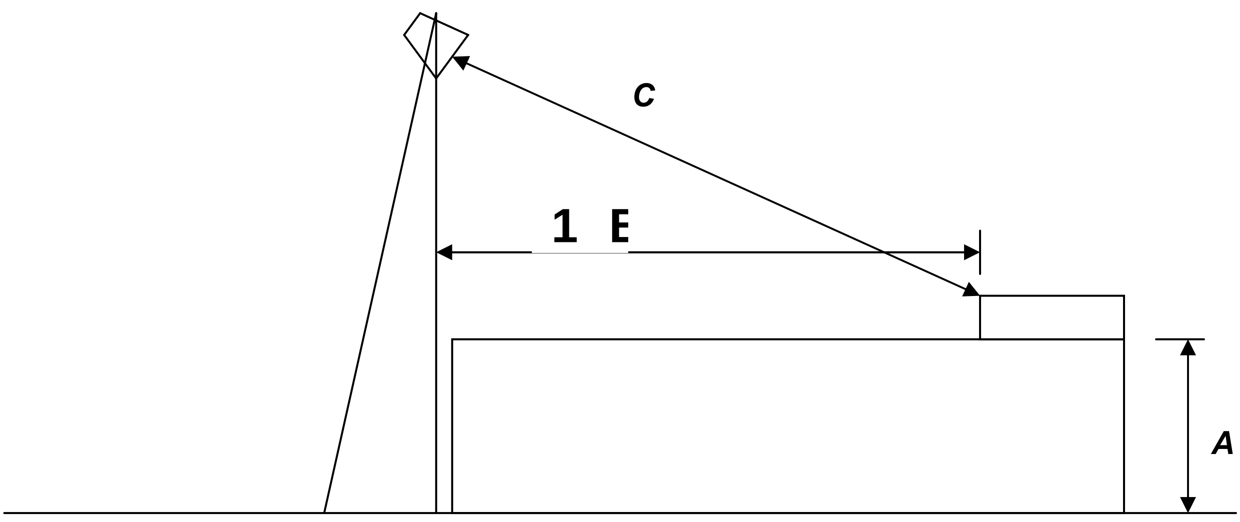
Place strobe light stand at the foot of the bed. Each strobe should be aligned directly towards the edge of the pillow and should be in line with the centre line of the expected body position.

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 H: Details of the blood alcohol testing equipment and procedure

BAC is normally measured and reported as *milligrams* of alcohol per 1000 millilitres (1 litre) of blood (mg/1000 mL). The breathalyser devices (Lion Alcometer S-D2) were recalibrated every 3 months to ensure accuracy of measurement. Victoria Police advised that the Lion Alcometre was a preliminary breath testing unit only, and that a confirmatory evidentiary measure of BAC (e.g. Via a blood sample) was also required when it was used by them.

The manual describes that the Lion Alcometer S-D2 measured the concentration of alcohol vapour in expired breath by using an electrochemical fuel cell which contained two platinum electrodes. This fuel cell generated a small voltage that was directly proportional to the amount of alcohol concentration present in breath that is drawn into the unit (Lion Laboratories, 1982). The exact specifications of the unit are reported below.

Model	Lion Alcometer S-D2
Detector	Electrochemical fuel cell
Specificity	Responds only to alcohol in breath and is unaffected by other possible contaminants, such as acetone
Accuracy	+/- 10mg per cent blood alcohol concentration around the calibrated level
Analysis time	Approximately one minute per test.
Dimensions	120 x 63 x 30mm

Adapted from Lion Alcometer Manual (Lion Laboratories, 1982)

Before breath testing a ‘ready check’ was performed to ensure the breathalyser fuel cell was completely free of alcohol. When a satisfactory ‘ready check’ had been completed, the researcher depressed the ‘set’ button on the breathalyser until it locked. A fresh mouthpiece was then attached to the sampling port of the unit and instructions were administered to the participant. A new mouthpiece was always used for each test. Participants were instructed to fill their lungs and blow into the lipped end of the mouthpiece tube strongly enough to illuminate light ‘A’, and to then continue blowing long enough to illuminate light ‘B’ when they would be told to stop. The researcher depressed the ‘READ’ button immediately after instructing the participant to stop, and continued to hold it down until the display stopped changing (approximately 15 to 20 seconds). The BAC was recorded from the display. Testing was repeated if the participant failed to provide sufficient breath to illuminate both sampling lights. If the alcohol reading was below .05 more alcohol was administered, followed ten minutes later by further testing. The amount of alcohol administered was once again estimated, and was dependent upon the previous BAC reading.

If the amount of alcohol required was overestimated and overshooting occurred the ST was instructed to carry out testing every 20 minutes until the participant’s BAC fell to the level of .04. At this time another dose of alcohol was administered and the usual procedure for measuring BAC was followed. It is known that BAC continues to rise rapidly before peaking at 30 to 60 minutes after a person’s last alcoholic drink. The BAC level then slowly decreases in a linear fashion at an average rate of about .015 per hour. This meant that the BAC of participants who had consumed the right amount of alcohol to reach .05 without overshooting would continue to rise for about 30 minutes after they went to bed. If the procedure for overshooting simply required waiting until the person’s BAC fell to .05 without administering any additional alcohol, then the person would be going to sleep on the downward slope of the alcohol absorption curve, rather than continuing to rise. Because the added inconvenience to participants that occurred as a result of overshooting was considerable, a tolerance level of +.01 BAC was allowed. This meant that several participants were measured at .06 prior to lights out.