Strobe Lights, Pillow Shakers and Bed Shakers as Smoke Alarm Signals

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ABSTRACT

This paper assesses the waking effectiveness of strobe lights and pillow and bed shakers as smoke alarm warning devices and compares them to an auditory signal. The signals were activated at increasing intensity levels during slow wave (deep) sleep in two groups, (i) 38 adults aged 18-77 years with hearing loss of 25-70 dBA in both ears, and (ii) 32 young adults aged 18 -26 years impaired with alcohol at 0.05 blood alcohol content. Three quarters of both groups slept through the strobe light activated at above the intensity required by the standard whereas a 75 dBA 520 Hz square wave T-3 sound woke over 90%, and at a louder volume 100%. The pillow and bed shakers did not wake 17-20% of the hard of hearing participants at the intensity level as purchased. Hard of hearing participants aged ≥60 years were less likely to wake up to the bed shaker than those aged <60 years. The pillow and bed shakers tested were not an effective means of waking moderately alcohol impaired young adults from deep sleep, with 36%-42% not waking up at the intensity level as purchased. For both groups the pillow and bed shakers were less effective than the 520 Hz square wave T-3 sound at 75 dBA at the pillow. This study supports earlier research showing that when sleep stage is assessed strobe lights have poor waking effectiveness. The 520 Hz square wave sound was more effective than the non-auditory signals for both groups.

KEYWORDS: smoke alarms, sleep, human behaviour in fire, strobes, pillow shakers, bed shakers

INTRODUCTION

Smoke alarms are intended to warn dwelling occupants of a fire so they are less likely to be killed or injured by the fire or its effects. Early warning is assumed to be beneficial, so quick detection and rapid occupant response is desired. It is likely that the greatest benefit occurs when the occupants are asleep [1]. Recent studies have shown that a 520 Hz square wave T-3 sound [2] is more likely to elicit a response (and a quicker response) than the standard Australian and USA smoke alarm sounds when at the same sound level [1,3-6]. The 520 Hz square wave T-3 sound at a lower sound level has been found to elicit the same probability of response as the standard sounds at considerably higher volume. But hard of hearing, deaf or alcohol impaired occupants (and perhaps others) may not become aware of a smoke alarm alert based on sound. Alternative means of notification include a strobe light and a pillow or bed shaker.

Many smoke alarms that combine a ~3100 Hz sound with a flashing strobe light have been installed in a range of buildings in the USA. Where such a device is installed in a sleeping area NFPA 72 [7] applies and requires 110 candela (cd) intensity if the strobe is mounted on the wall ≥610 mm below the ceiling or 177 cd if the strobe light is mounted on or <610 mm from the ceiling. These devices are marketed as being suitable for the deaf and the hard of hearing.

In 2005 a British Standard BS 5446-3 [8] was published which contained specifications for smoke alarm 'kits' for deaf and hard of hearing people. This standard requires that any smoke alarm kit for deaf or hard of hearing people incorporates a standard UK auditory smoke alarm as well as a combination of a vibration pad (for placement under the pillow or mattress) and flashing light. The flashing light is required to be white with an effective light intensity ≥15 cd.

The earliest study using a strobe was conducted by Nober et al. [9] but stage of sleep was not assessed. Twelve deaf and ten normal hearing subjects were tested while asleep using industrial and household strobes (100 cd, 1.25 Hz) and a 100 W flashing light bulb. The strobes performed equally, but the light bulb was much less effective. The deaf and normal-hearing participants awoke to the industrial strobe 92% and 70% of the time respectively. In 1991 Underwriters Laboratory tested a strobe on 22 sleeping deaf adults (aged 20–65+ years) and students (58 aged 13–19 years and 14 aged 10–12 years) between 1-4 am without stage of sleep being assessed. The 110 cd strobe flashing for four minutes was 86%, 91% and 100% effective respectively [10].

Bowman, Jamieson and Ogilvie [11] found only 35% of 13 normal hearing females (ages 18+ years) were awoken from stage 3 or 4 sleep by a ≥75 cd strobe presented for five minutes, while 45% awoke from REM sleep. In a study by Du Bois et al. [12] a 110 cd, 1 Hz strobe for two minutes woke >57% of 32 deaf adults, 34% of 45 hard of hearing adults and 32% of 35 normal hearing adults.

Based on these studies it appears that sleeping deaf people may be more sensitive to a strobe than hearing-able people and that controlling for sleep stage results in lower rates of waking.

A range of alarm products using a tactile signal are marketed primarily to hard of hearing and deaf people. They are a small device that vibrates, with some marketed for placement under either the mattress or the pillow (termed bed shakers here), while others are marketed for placement only under the pillow (pillow shakers). They are similar in size, shape and the low level sound volume associated with the spinning weight inside the device. Three studies report responsiveness to a tactile alarm. In 1991 Underwriters Laboratory reported a study using bed vibrators [10]. A cylindrical vibrating device with a displacement of ~3 mm at 100 Hz was placed under either the pillow or the mattress (~centre of torso) and activated from 1-4 am without assessment of sleep stage. The four minute presentation woke 95% of 20 legally deaf adults in both positions. The awakening rate among 72 deaf 10-19 year olds varied from 77-100% depending on age group.

In a 1995 study the effectiveness of an off-the-shelf bed shaker (L'il Ben SS12) was tested when placed under the mattress [13]. This study involved 11 hard of hearing adults aged 20-76 years, with hearing loss ranging from slight to profound, and 16 young adult university students with normal hearing wearing ear plugs. Of the normal hearing group, 92% woke quickly (within one minute) from REM sleep, and 76% awoke quickly from slow wave sleep (SWS). The hard of hearing adults were similar (87% awoke from REM sleep and 70% from SWS), but some were slower, with 19% requiring >1 minute to wake up. Du Bois et al. [12] found that the waking effectiveness of a continuous bed shaker (apparently placed under the mattress) varied: 92% of 34 hearing able adults, 82% of 45 adults with partial hearing and 93% of 32 deaf adults. Bed shakers with an intermittent pulse were 100% effective for all hearing levels, even from deep sleep.

The research reported here extends two earlier reports [4, 5] with new data comparisons focusing on investigating the waking effectiveness of strobe lights and pillow and bed shakers in two populations:

- adults aged from 18 to 80 years with mild to moderately severe hearing loss (but not severe or profound hearing loss), termed hard of hearing (HH)
- young adults (18 to 26 years) who were moderately impaired with alcohol (0.05 BAC), termed alcohol impaired (AI)

Specific research questions addressed for each of these populations (HH and AI) include:

- Does a strobe light provide an effective means of waking up from deep sleep?
- Are pillow and bed shakers an effective means of waking them from deep sleep?
- Are there any sex differences in arousal thresholds to the different signals?
- Are there any differences in arousal thresholds for different signals in those aged below 60 and those aged 60 years or more?

In this study all devices presented a pulsating signal in the same form, as far as possible, as the T-3 signal, as set out in ISO 8201 [2]. The decision to only test a pulse pattern was based on the desire of the fire safety community in the USA, Canada and Australia to make the T-3 the fire evacuation signal and to make it different from other signals (e.g. telephone, doorbell).

METHOD

Participants

A total of 70 participants were tested. They:

- met the specified hearing screening criteria
- reported that they do not regularly take medication that affects their sleep, do not have a sleep disorder, and do not normally have difficulty falling asleep
- reported that they do not have any major physical or neurological conditions that may affect their ability to perceive or respond to a visual, tactile or auditory signal (apart from hearing impairment for the hearing impaired group)

Compensation for inconvenience was $80 AUS per night with a $75 bonus paid after completion of the study.

The thirty eight adults who were hard of hearing (16 male, 22 female, mean age = 54.4, SD = 16.0, age range = 18-77 years) had a hearing loss of ≥25 dB and ≤70 dB in both ears, with the hearing loss being based on the pure tone average of thresholds at 500, 1000, 2000 and 4000 Hz. This is described as having mild to moderately severe hearing loss. Most of these participants wore a hearing aid when not asleep.

The 32 young adults (15 male, 17 female, mean = 21.2, SD = 2.6, age range = 18-26 years) in the alcohol impaired group had normal hearing (≤20 dBA loss in both ears at the frequencies listed above).

Apparatus

Testing of hearing loss used an audiometer (Endomed SA 201/2 #13355) with specialized headphones to allowed field testing in quiet environments. The signal was delivered for a 30 second period at a nominated starting intensity and increased in steps after a short silence.

The strobe was presented at three levels of intensity, 177, 210 and 420 cd. These intensities resulted from presenting one, two or three strobes simultaneously. NFPA 72 requires strobes to pulse with a frequency between 1 and 2 Hz [7] and this study used a modified T-3 pattern of three flashes over one second with a gap of 1.5 seconds between each set of three flashes. The strobe lights were mounted vertically 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. Figure 1 includes a photo of the three strobes when set up.

Two tactile devices were used. The pillow shaker was the “Visit” bed shaker from Bellman and Symfon (recommended for placement under the pillow) and the bed shaker was the Vibralarm VSS12. Both devices vibrated with vertical and horizontal displacements generated by an off-centre spinning weight. The bed shaker was placed under the mattress under the sleeper’s navel region. The pillow shaker, inside a small linen bag, was attached to the underside of the centre of the sleeper’s top pillow with a safety pin. This was consistent with the recommended placement discussed within the local deaf community. Both tactile devices were adapted so that each had five intensity levels. The intensity of each shaker when it came “off the shelf” was just below level 3, with level 1 the lowest intensity and level 5 the highest (Table 1). Both tactile devices were modified to a T-3 pulsing pattern. Both shakers made a slight noise, which was especially audible when the device was under the pillow. No differences were found in arousal threshold to the tactile devices as a function of any variations in bed and pillow type. Photos of the bed and pillow shaker are also shown in Figure 1.

Table 1. Intensity of pillow and bed shakers at each level.

Signal	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Pillow shaker	0.086 ms^{-2}	0.187 ms^{-2}	0.258 ms^{-2}	0.294 ms^{-2}	0.533 ms^{-2}	0.533 ms^{-2}
Bed shaker	1.09 ms^{-2}	1.56 ms^{-2}	1.91 ms^{-2}	2.10 ms^{-2}	2.41 ms^{-2}	2.41 ms^{-2}

The 520 Hz square wave and ~3100 Hz pure tone auditory signals were presented via a speaker placed 1 m from the middle of the pillow. The latter is the signal used in current smoke alarms. The spectral properties of both have been described previously [4,5].

Polysomnographic recordings were conducted using Compumedics Siesta data acquisition systems monitored by a sleep technician in another part of the house. 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. A few chose to sleep in the Victoria University Sleep Laboratory.

The alcohol used for the alcohol impaired study was vodka mixed with unsweetened reconstituted orange or cranberry juice. Lion Alcometre S-D2 breathalysers were used to measure blood alcohol content (BAC).

Procedure

Each participant was administered a hearing screening test prior to the sleep testing. Those who met the criteria were assigned to a sleep technician who made the sleep testing arrangements. During this contact the importance of avoiding alcohol on the day of testing and ensuring sufficient prior sleep were emphasized.

Data was collected by the sleep technician. In the overall study six signals were tested across two nights (three signals per night as far as possible). Three of the signals were auditory, only two of which are relevant to this paper. Signals were presented in a counterbalanced order and testing nights were usually a week apart. All equipment was set up on both occasions to minimize priming effects. Electrodes were attached according to the standard placement set down by Rechtschaffen and Kales [14]. For the alcohol impaired research alcohol was administered before and during electrode application.

Fig. 1. The strobe lights and the pillow and bed shakers.

After lights out the sleep technician monitored the participant EEG output until slow wave sleep (SWS, stage 3 and/or 4) was confirmed for a minimum of three consecutive 30 second epochs. The system was then activated to start the required stimulus at the lowest experimental level. For the hard of hearing participants awakenings were from either stage 3 or stage 4 (as the duration of stage 4 sleep declines with age), while the alcohol impaired awakenings were from stage 4.

Each signal was presented in discrete episodes of 30 seconds. If the participant continued to sleep a pause occurred. 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 a bedside button three times. If they did not wake to the highest signal intensity then, after the normal pause, the highest signal intensity was played for a further three minutes. Thus they would receive the maximum intensity of the signal for a total of three and a half minutes. All signals at each intensity level commenced from a nil intensity, simulating the sudden onset of an emergency signal. Table 2 gives the intensity measurements at each level for the auditory and tactile signals. To ensure that all signals were presented across the identical time frame the pauses between the levels of strobe intensity were longer.

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

For alcohol impaired participants breath testing was conducted ten minutes after the first alcoholic drink was completely consumed. After the required blood alcohol level (BAC) was reached (0.05 BAC + 0.01, - 0.00) participants were settled into bed.

Table 2. Temporal specifications of signal delivery.

Type	***Number of levels***	***Lowest intensity***	***Highest intensity***	***Signal on duration***	***Signal off duration***	***Total time***
Sounds	5	55 dBA	95 dBA	30 sec	30 sec	8 min
Shakers	5	See Table1	See Table 1	30 sec	30 sec	8 min
Strobe lights	3	177 cd	420 cd	30 sec	70 sec	8 min

RESULTS

The primary interest in these experiments was the proportion of the tested groups waking up at the various intensity levels of the signal. This waking data for the strobe lights are presented in Table 3 and for the pillow and bed shakers in Table 4.

Table 3. Frequency and percentage statistics for awakenings with strobe lights at each level for the hard of hearing (HH) and alcohol impaired (AI) studies.

Description	***HH***		***AI***	
	n/N	***%***	***n/N***	***%***
Awoke at 177 cd	10/38	26%	6/25	24%
Awoke at 210 cd	4/38[a]	11%	7/25	28%
Awoke at 420 cd	5/38	13%	2/25	8%
Awoke during extended 420 cd	2/38	5%	2/25	8%
Slept through	16/38	42%	8/25	32%

[a] A participant awoke during the silence immediately following this signal and they were deemed to have woken during the preceding signal.

Table 4. Frequency and percentage statistics for awakenings with pillow and bed shakers at each level for the hard of hearing (HH) and alcohol impaired (AI) studies.

Description	**Pillow shaker**				**Bed shaker**			
	HH		***AI***		***HH***		***AI***	
	n/N	**%**	**n/N**	**%**	**n/N**	**%**	**n/N**	**%**
Awoke at Level 1	21/30[a]	70%	9/19	47%	20/35	57%	12/28	43%
Awoke at Level 2	2/30	7%	2/19	11%	8/35	23%	4/28	14%
Awoke at Level 3	2/30	7%	0/19	0%	0/35	0%	2/28	7%
Awoke at Level 4	1/30	3%	1/19	5%	1/35	3%	3/28	11%
Awoke at Level 5	0/30	0%	0/19	0%	1/35	3%	0/28	0%
Awoke during Level 6	3/30	10%	1/19	5%	1/35	3%	0/28	0%
Slept through	1/30	3%	6/19	32%	4/35	11%	7/28	25%

[a] A participant awoke during the silence immediately following this signal and they were deemed to have woken during the preceding signal.

Cumulative frequency graphs comparing the total percentage of each group woken up by each of the signals at each signal level are shown for the hard of hearing in Figure 2 and for the alcohol impaired in Figure 3. For comparison, also shown in these figures are the best (520 Hz square wave) and worst (~3100 Hz current smoke alarm sound) of the sounds tested during this research program. In these figures the levels of the auditory signals are numbered 1 to 5. These levels correspond to the 30 second presentations at 55, 65, 75, 85 and 95 dBA respectively. Level 6 is the subsequent three minutes at 95 dBA. For the strobe lights levels 3 to 5 correspond to 30 second presentations at 177, 210 and 420 cd respectively. Level 6 is three minutes at 420 cd intensity. Similarly, for the pillow and bed shakers the levels are the five levels mentioned above. The graphs are organized such that level 3 corresponds to the intensity level closest to the recommended standard (for the sounds and strobes) or the "as bought" level for the pillow and bed shakers. Thus for the auditory signals level 3 is 75 dBA (often recommended as the intensity at the pillow) and for the strobe lights it is 177 cd (where the NFPA standard for a wall mounted strobe light is 110 cd).

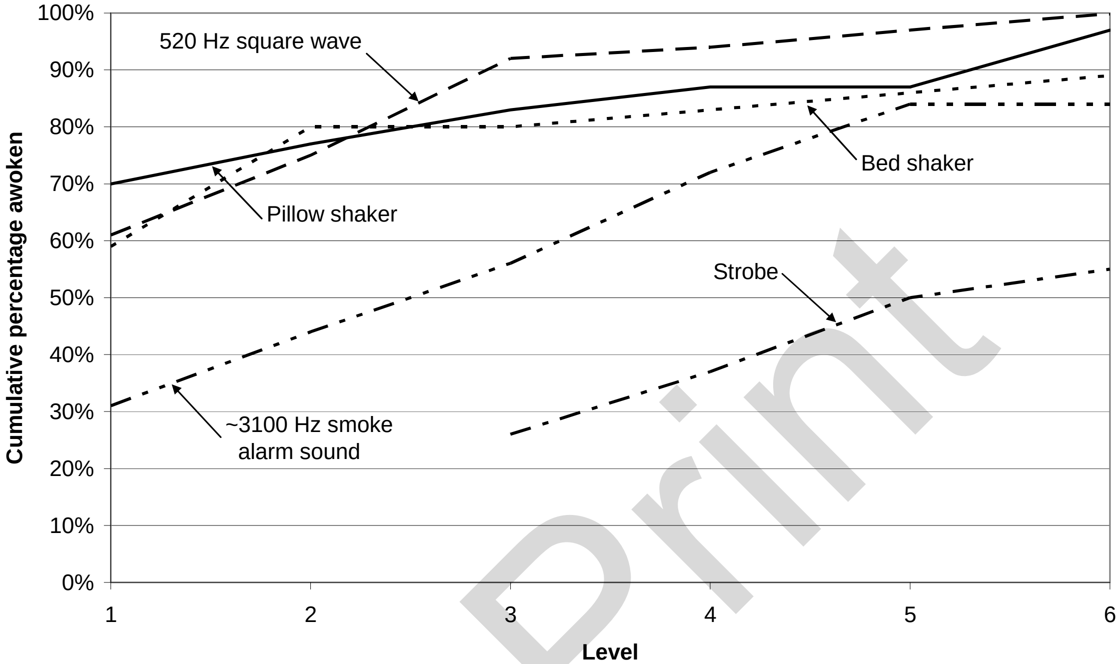

Fig. 2. Cumulative frequency graph of waking up to signals for hard of hearing participants.

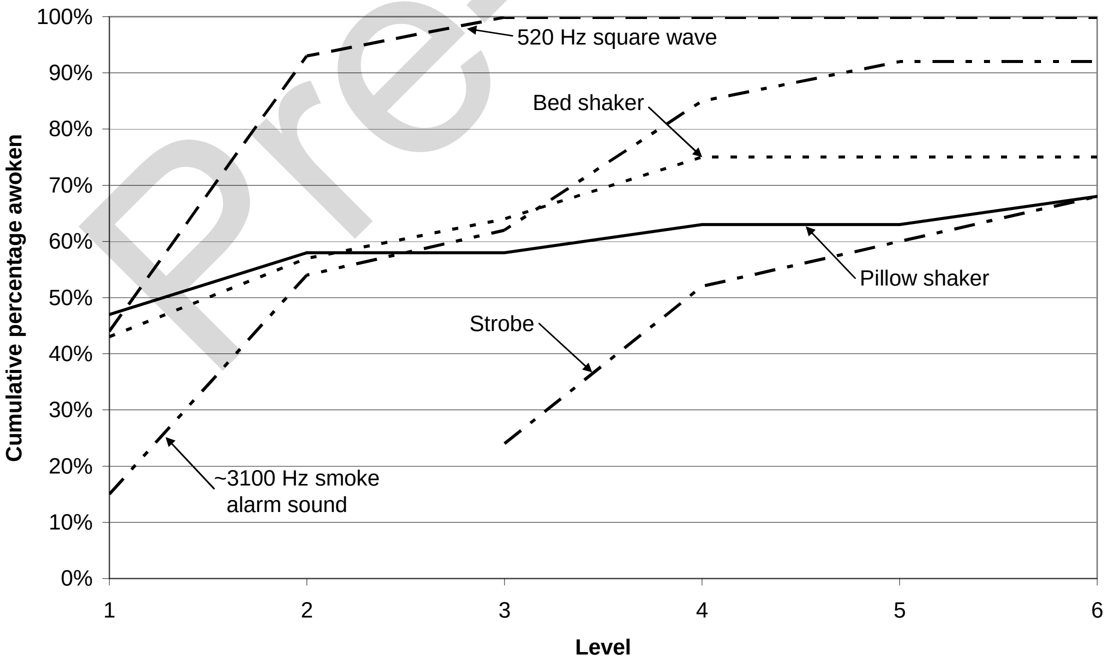

Fig. 3. Cumulative frequency graph of waking up to signals for alcohol impaired participants.

The results in Table 3 reveal that the strobe at the reference level (177 cd) woke only a quarter of the participants in both the hard of hearing and alcohol impaired groups, and only 58% and 68% of the hard of hearing and alcohol impaired participants during the entire 8 minute exposure. The results in Table 4 show that both the bed and pillow shakers were much more effective at the reference level (as purchased for the pillow and bed shakers) (84% woke up for in the hard of hearing group and 58% in the alcohol impaired group for the pillow shaker and 80% in the hard of hearing group and 64% in the alcohol impaired group for the bed shaker). The shakers were also much more effective after the entire exposure for the hard of hearing group (the pillow shaker waking up 97% and the bed shaker 89%), and more effective, but by a smaller margin, for the alcohol impaired group (the pillow shaker waking up 68% and the bed shaker waking up 75%).

The graphs in Figures 2 and 3 both show that the effectiveness of the 520 Hz square wave auditory signal at the reference and higher levels was superior to that of all of the other signals. The poor effectiveness of the strobe lights for both the hard of hearing and alcohol impaired groups is also apparent in these figures.

No significant difference in response with gender or age was found in either study except that for the hard of hearing study when the group was split between those less than 60 years of age and those 60 or more years there was a significant difference for the bed shaker. The results suggest that the bed shaker is significantly less effective for those aged 60 or more years of age.

DISCUSSION

The most important property of smoke alarm signals is the proportion of people who are not woken up. These are the people most likely to be injured or killed in a fire. Thus it is clear that although all intensity levels of the strobe lights were above the level as required in the NFPA standard [7] they were very ineffective. It was found that ~75% of both hard of hearing and alcohol impaired groups did not wake up to the lowest intensity level and 42% for hard of hearing and 32% for alcohol impaired did not wake up to the extended duration at the highest intensity. This result is consistent with the two previous studies that controlled for sleep stage [11,12], both finding that more than two thirds of their normal hearing participants slept through a strobe that was less intense than the lowest intensity level in the present study. The findings of the current study do not support the use of even very high intensity strobes to awaken hearing-able people (i.e. with hearing threshold levels of less than 70 dBA).

It is apparent in Figures 2 and 3 that the 520 Hz square wave signal was the most effective signal waking 92-100% of the people in each sample (hard of hearing and alcohol impaired respectively) at or below the reference level (75 dBA). In contrast the ~3100 Hz sound (the current smoke alarm sound) awoke only 58% of participants at this level.

The results for the hard of hearing group show that the pillow and bed shakers were much more effective than the strobe with 3% sleeping through all levels for the pillow shaker and 11% sleeping through with the bed shaker. At the "as purchased" intensity level, the results indicate that for the pillow shaker 17% would sleep through and for the bed shaker this would be 20%. These results are not inconsistent with the results reported by Murphy et al. [13] where 30% of their hard of hearing adults slept through when the tactile signal was presented in slow wave sleep and 24% of their normal hearing participants also slept through.

The results for the alcohol impaired group are less favorable for the shakers, showing that, under the testing conditions, 32% slept through all levels for the pillow shaker and 25% slept through with the bed shaker. At the "as purchased" intensity level, the results show that for the pillow shaker 58% slept through and for the bed shaker 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% [10,13,12]. The results of Du Bois et al [12] 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). However, the conclusion from the current study is that the pillow and bed shakers are not effective for waking moderately alcohol impaired participants, either at the off the shelf intensity level of the bed and pillow shakers, or at higher intensities.

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 shaker, 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.

In trying to extrapolate the percentage of people woken up by each signal in these studies, compared to what may be expected in the field there are several factors that must be considered. Two factors likely to exert a strong influence making any absolute values (such as sound levels, intensities and percentages responding to signals) under-estimations are priming and the screened/controlled sample. All of the participants were expecting to be exposed to various signals to test if this would awaken them (i.e. they were primed). Previous work has shown that such an expectation, which increases signal meaningfulness, increases the likelihood of waking up [15]. Also, in order to reduce the potential effect of confounding variables, the participants for a sleep study such as this were highly selected. Not only were the hearing criteria quite stringent, any adults that were taking medication affecting sleep were excluded. In addition, the participants were carefully instructed to avoid certain factors that may increase their chance of not waking up. These included prior sleep deprivation (including shift work) and any non-administered alcohol. In a field population such confounding factors are likely to occur quite regularly and could increase arousal thresholds, especially in the first half of the night. Nevertheless, as all the signals were tested under the same experimental conditions and in a way to minimize the uncontrolled effect of individual differences or night to night variations, comparative conclusions as to efficacy across signals can be expected to be valid.

CONCLUSION

Strobe lights, presented alone, were not an effective means of waking either of the two population groups tested. Under the testing conditions three quarters of the people in the hard of hearing and alcohol impaired groups did not wake up to the lowest strobe light intensity, which was more intense than that required by NFPA 72 [7]. Thus it is not appropriate to recommend strobe lights, either alone or in tandem with the current high pitched smoke alarm, as an effective means of waking people whose hearing loss is less than moderately severe (i.e. hearing thresholds of less than 70 dBA) or who have even a low (0.05) blood alcohol level.

Under the testing conditions the pillow and bed shakers, presented alone, did not wake 17-20% of the hard of hearing participants at the intensity level as purchased (vibrating in intermittent pulses) and those hard of hearing participants who were aged 60 years or more were less likely to awaken to the bed shaker than those aged below 60 years. No age group differences were found for any other signal. The pillow and bed shakers 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. At the intensity level as purchased 36%-42% did not wake up.

These studies add to previous research suggesting a low frequency square wave (with a fundamental frequency of 520 Hz or thereabouts) is the most effective alerting signal tested to date and would be an appropriate emergency alerting device for those with hearing loss within the range tested in this study.

Further study should be undertaken with people with higher levels of hearing loss (including deaf people) to determine the best signals, or combination of signals, that will reliably awaken this population from deep sleep. This should include bed shakers, pillow shakers, low frequency square waves (beneficial for those with residual hearing) and perhaps could include strobe lights.

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