Optimizing Emergency Awakening to Audible Smoke Alarms: An Update

Dorothy Bruck and **Michelle Ball,** Victoria University, Melbourne, Australia

Objective: This review examines research on arousal from sleep in an emergency. It considers whether the current smoke alarm signal is optimal for waking those most at risk of dying in a fire and, if not, how it may be improved. **Background:** The fire fatality rate during the sleeping period is approximately three times greater than at other times. **Method:** Four key areas are reviewed: (a) the characteristics of four signals (high-frequency beeping, Temporal 3, voice, and naturalistic sounds); (b) how human characteristics alter arousal to different signals; (c) research comparing the effectiveness of different alarms in different sleeping populations; and (d) acoustical, methodological, and theoretical implications. **Results:** Significant risk factors for staying asleep include high levels of background noise, being a heavy sleeper, sleep deprivation, being a child, hypnotics, alcohol intoxication, and hearing impairment. The high-frequency beeping signal was significantly less effective than either a voice alarm or mixed-frequency beeping in waking selected at-risk groups. **Conclusion:** The alternative signals were more effective in arousing various groups of sleepers than was the high-frequency signal currently used in smoke alarms. **Application:** Replacement of the current smoke alarm signal with one of a lower frequency is likely to wake more people more quickly and save lives.

INTRODUCTION

Since the widespread introduction of residential smoke alarms in the 1970s, there has been one review about sleep and smoke alarms (Bruck, 2001) that drew together factors known to affect responsiveness during sleep to auditory signals, studies on arousal to high-pitched beeping alarms, and fire fatality statistics. It was concluded that many groups in the population would be unlikely to awaken to a 75-dBA high-pitched alarm (at the pillow) and that some of these groups were overrepresented in fire fatality statistics.

Since that time a series of studies have been published that compared the auditory arousal of participants to different signals under different conditions. These studies have yielded important and surprising results, initiated discussions within fire regulatory bodies around the world, and prompted a reevaluation of whether the current signal used in smoke alarms is optimal for waking those most at risk of dying in a fire. This update brings together literature to help inform such a reevaluation, considers the implications of the new findings, and highlights areas requiring further research.

Over the last three decades fire services in many countries have made the promotion of residential smoke alarms their main community safety message. Analyses of fire fatalities show that being asleep is clearly a risk factor for dying in a residential fire, with reports from different countries suggesting that between 46% and 86% of all fire victims were sleeping at the time of the fire (Brennan, 1998; Sekizawa, 1991; Thomas & Brennan, 2002). Despite many more fires occurring during daylight hours, the death rate for apartment fires during the sleeping period (1:00–7:00 a.m.) is three times greater than at all other times (Thomas & Brennan, 2002). Statistical studies of the predicted number of lives saved by smoke alarms suggest that they are effective (Ahrens, 2004; Norris, 2004).

However, 20.3% of U.S. home fire deaths occurred in homes where a smoke alarm was present and operated (Ahrens, 2004), and this means

Address correspondence to Dorothy Bruck, School of Psychology, Victoria University, P.O. Box 14428, MCMC Melbourne 8001, Australia; dorothy.bruck@vu.edu.au. ***HUMAN FACTORS,*** Vol. 49, No. 4, August 2007, pp. xxx–xxx. DOI 10.1518. XXXXXXXXXX.

some 770 people die annually in the United States despite their smoke alarm (Fahy & Molis, 2004). Clearly some of these fatalities arise from scenarios in which smoke alarms cannot play a role (e.g., ignition of clothing or children hiding in fear) or in which the occupants were too injured or disabled to escape in time. Nevertheless, in some cases a smoke alarm may not arouse the sleeping occupants in time to escape, and a lack of response or a delayed response clearly increases the chance of dying in a fire (Thomas & Brennan, 2004). This raises several important questions. Can one predict who will awake to a smoke alarm and who will sleep through? Is the current smoke alarm signal optimal for waking up those most at risk of sleeping through, and if not, how can it be improved?

This review will consider the research and issues important in addressing these questions within four major sections. First, studies suggest that different auditory signals differ substantially in their waking effectiveness. Important factors within the signal that affect arousal thresholds will be discussed and the characteristics of different beeps, voice messages, and naturalistic sounds considered in detail. Second, it is known that a range of different human characteristics will alter the ability to wake up to sounds. The literature on what these characteristics are and their relative importance will be examined. The third, most extensive, section will consider the empirical research comparing the effectiveness of different alarms in different populations. Finally, issues for future research are highlighted within sections covering the acoustical implications of different alarms, methodological concerns, and a theoretical framework.

SIGNAL SIGNIFICANCE AND CHARACTERISTICS

Contrary to popular belief the brain does not “shut down” during sleep, people continue to monitor the environment and selectively respond. Discrimination between different signals clearly occurs during sleep, showing that the arousability of an auditory signal is not simply a function of how loud it is.

Signal Significance

Because cortical analysis of the meaningfulness of a signal precedes arousal, people respond selectively to signals, depending on the level of significance to them. An early study found that sleeping participants responded more often to their own name than to other names (Oswald, Taylor, & Treisman, 1960). Significance can be added to a signal by “priming” the person to respond to some signals (e.g., a doorbell) but not to others (e.g., a telephone). When participants were primed to respond to a certain signal presented during the deepest stage of sleep, awakenings increased from 25% to 90% (Wilson & Zung, 1966). Clearly, signal significance and interpretation will affect arousal likelihood, and thus it is important that any emergency signal has a unique sound quality that allows it to be easily discriminated from other electronic beeping sounds in the environment (car alarms, mobile phones, microwave ovens, etc).

It has been found, using functional magnetic resonance imaging technology (Portas et al., 2000), that sounds that have an emotional significance have lower arousal thresholds and an increased probability of waking up a person. During sleep, presentation of a participant’s name activated the left amygdala and left prefrontal cortex. It was hypothesized that the amygdala directly processed the emotional significance of the name and that this activated the prefrontal cortex. The involvement of a “pathway of learned fear” was suggested, with a key implication being that during sleep the emotional content of a signal may be processed independently of cortical input about the meaning of the signal. Thus the use of sounds that arouse people’s emotions may be an important consideration in emergency signals.

Signal Characteristics

There is now an important body of literature about auditory alarms signals and their interpretation by individuals when awake (Edworthy, Loxley, & Dennis, 1991; Edworthy & Stanton, 1995), and this has led to design criteria suggestions to improve the effectiveness of emergency notifications in awake populations. However, when residential smoke alarms were first developed and widely distributed in the 1970s, the focus was on the technology to detect heat and/or smoke and little attention was paid to the nature of the signal.

As noted by Berry (1978), the issue of the audibility of fire warning equipment was relegated to an appendix of the National Fire Protection Association (74-1975), and the assurances about the ability of the signal to awaken people that were provided in the appendix were at variance with the published auditory threshold data available at the time. Now the standards in various countries may specify a minimum threshold at the pillow, such as 75 dBA (e.g., the United Kingdom, Australia, and the United States). Standards do not normally have any requirements about the frequency of the smoke alarm signal used to notify a fire emergency. Four types of alarm signals will be considered here: the high-frequency beeping alarm, the Temporal 3 pattern, voice alarms, and naturalistic sounds.

A high-frequency beeping noise is the most widely available smoke alarm signal. It was most likely chosen for residential smoke alarms because high frequencies are rare in the normal environment and thus are likely to be more easily differentiated from other sounds. In addition, they are subjectively piercing and not easily ignored, and small battery-operated devices can easily generate such sounds using a piezoelectric. Most residential smoke alarms emit beeps of a single high frequency, which may be between 3000 and 5000 Hz (Ashley, Du Bois, Klassen, & Roby, 2005; Ball & Bruck, 2004a; Nober, Peirce, & Well, 1981a) with a sound intensity in the vicinity of 85 dBA at 10 feet (~3.05 m). Earlier smoke alarms sometimes combined two modulating signals peaking at 2000 and 4000 Hz (Kahn, 1984).

However, a high-frequency signal appears to have several drawbacks. The most obvious disadvantage is that people with high-frequency hearing loss (a part of normal aging) will have more trouble hearing the signal (see the subsection on impaired adults in the Awakenings With Various Alarm Signals section). A further disadvantage of a high-frequency signal is that high frequencies are more easily reduced by doors and walls than are frequencies below 500 Hz. That is, sound absorption is lower at low frequencies and higher at high frequencies (e.g., above 2000 Hz). Figure 1 shows transmission losses in dB as a function of the frequency of the sound being absorbed for a conventional wood stud wall with gypsum board. It can be seen that transmission losses vary by nearly 30 dB, depending on whether the frequency of the sound is low or high.

Robinson (1986) reported that the sound loss from the corridor to the room with the door open was about 12 dB for all frequencies above 500 Hz, with the closure of a door typically contributing another 15 dB, increasing to 20 dB if the door's edges were sealed. These data suggest it would be impossible for a 90-dB smoke alarm located in the hallway to reach the pillow at 75 dB if the door was closed. Similarly, others have reported that a hallway smoke alarm will penetrate a closed bedroom door with a resulting bedside volume of between 51 and 68 dBA, depending on the room configuration and materials (Nober, Peirce, & Well, 1981b).

In various Western countries fire alarms are

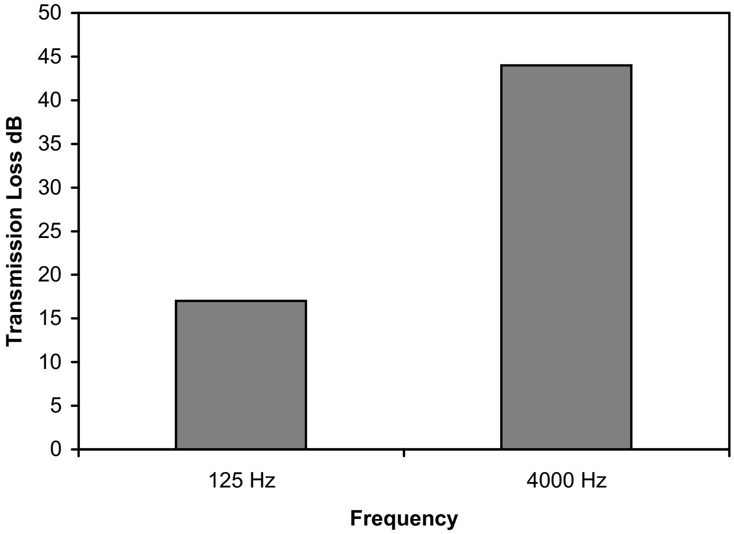

Figure 1. Sound transmission losses as a function of frequency of the sound and surface mass (in kg/m^2) of the material through which the sound is being transmitted. (Data from Quirt, 1985.)

now being sold that emit the Temporal 3 (T-3) pattern. International standard ISO 8201-1987 (Acoustics – Audible Emergency Evacuation Signal; International Organisation for Standardisation, 1987) defined the T-3 signal, and this was adopted by the U.S. National Fire Protection Agency (NFPA 72), Underwriters Laboratories (UL217), and the Building Code of Canada in the mid-1990s as the required fire alarm signal in building fire warning installations. The Australian Standard adopted the ISO 8201-1987 as the required fire occupant warning signal in 2004 (AS 1670.1).

One cycle of the temporal pattern of the T-3 evacuation signal is as follows: signal on for 0.5 s, signal off for 0.5 s, signal on for 0.5 s, signal off for 0.5 s, signal on for 0.5 s, and signal off for 1.5 s. The international standard does not limit the fire alarm signal to any one sound, so signals of different frequencies and acoustic characteristics can be used within the T-3. The aim is that people will recognize the specific timing pattern as the signal to evacuate immediately.

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

There is a considerable body of literature about the possible use of the human voice in alarm signals. The appeal lies in the fact that a voice can directly convey both meaning and emotional significance. Individuals hearing voice messages can successfully identify the emotions intended (Banse & Scherer, 1996). Moreover, the words used and the manner in which the words are spoken can influence their believability, appropriateness, and sense of urgency (Edworthy, Clift-Matthews, & Crowther, 1998; Hellier, Edworthy, Weedon, Walters, & Adams, 2002).

It has been argued that humans have a particular cognitive specialization for speech perception (Liberman & Mattingly, 1989). Phonetic perception may be immediate, with no translation of patterns of pitch, loudness, and timbre being necessary. Language, unlike other forms of communication, may operate at a level that is precognitive. If this is the case when awake, then humans may also be particularly tuned to speech sounds during sleep.

A higher pitch is associated with a more intense emotion (Bachorowski & Owren, 1995), and the female voice is correspondingly assessed as more urgent than a male voice (Hellier et al., 2002). Infants have been found to be selectively more responsive to tones at lower frequencies (Weir, 1976), perhaps because these are associated with human speech. The parameters of pitch of human speech show it to be a complex sound, generally below 2500 Hz. One recording of a female voice as an alarm (Ball & Bruck, 2004a) was shown to have dominant tones at 400, 1600, and 2000 Hz. Prerecorded voice messages have been shown to be helpful in encouraging people to evacuate, and studies of warnings in large public spaces such as train stations (Proulx & Sime, 1991) show that a live directive voice announcement is highly effective.

Clearly, such an announcement overcomes people's concern that it might be a false alarm. The key disadvantage of a voice alarm is that the signal must be designed to meet standards for both audibility and intelligibility (Grace, Woodger, & Olsson, 2001). In addition, the speakers required to produce a quality, loud voice may not be able to be housed in the current small smoke alarm units.

Innovative research has used Gibson's (1979) theory of perception and information processing to test whether alarms that closely match their naturalistic intention or meaning are more effective than the more usual beeping signals. In an intensive care ward within a hospital, alarm signals were developed that closely matched the emergency situation they were aiming to alert staff about (Stanton & Edworthy, 1998). It was found that the naturalistic alarm signals were more effective than the standard signals in alerting novice medical staff who had little or no training of the standard signals.

Building on this research, Ball and Bruck (2004b) set out to design a more meaningful, perhaps also emotional, signal. The first stage of this was to ask people which sounds would (a) make them feel a negative emotion, (b) draw their attention when sleeping, and (c) make them feel the need to investigate upon awakening. Collating 1,447 responses showed that for all three questions people overwhelmingly nominated sounds within three categories: expressions of human emotion, such as a baby crying or a person screaming; manufactured alerting sounds, such as a smoke alarm; and other sounds that may naturalistically alert them to the possibility of danger, such as the sound of footsteps.

Two new sounds (conveying either emotional or naturalistic signals) were developed with the aim of testing their ability to awaken sleeping people in a fire emergency. As the naturalistic sound needed to be situationally congruent and indicate a fire, a signal consisting of house fire sounds (fire crackling, roaring, and popping, together with glass breaking) was developed. For a signal conveying human emotion, ethical considerations ruled out using genuine sounds of human distress. The second signal developed was a female actor's voice conveying human emotion through an urgent voice tone and choice of words ("danger," "fire," etc). The testing of these signals will be described in the section on adults waking to various alarms.

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

It is not unusual for fire alarms in buildings to move through a signal shift, or a series of different signals, such as beeping tones with different temporal and frequency patterns and whooping tones. Although it has not previously been investigated, anecdotally such shifting makes sense, as a signal that is constantly changing is likely to attract attention (whether one is awake or asleep). Sometimes people can sleep while a TV is on, only to wake up when it is turned off. The change in auditory signal, even to silence, may induce arousal.

Moreover, studies of auditory arousal thresholds (see the Human Characteristics section) consistently note major individual differences in thresholds, and it is possible (but not established) that different people may respond better to different signals and that shifting signals increase the chance that one of the signals will be perceived more easily by some people and acted upon. To date only one study (Ball & Bruck, 2004b) has tested the efficacy of a signal shift pattern in sleeping individuals, and this will be discussed below in the subsection on adults in the Awakenings With Various Alarm Signals section.

HUMAN CHARACTERISTICS

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

Of all the possible variables, it seems that individual differences account for the most difference in auditory threshold. One study examined responsiveness to a 5-s 800-Hz tone during sleep (Zepelin, McDonald, & Zammit, 1984) in people in various adult age categories, across three different stages of sleep (rapid eye movement [REM], Stage 2, and Stage 4). It was found that the thresholds varied for each age and sleep stage data point by at least 54 dBA, with the largest range being 82 dBA (i.e., range from 39 to 121 dBA for people in their 40s being awoken from Stage 2).

It is known that people's individual susceptibility to being awoken is quite consistent from night to night and within a night and that those who tend to sleep more deeply will do so in every stage of sleep, relative to those who sleep more lightly in all stages of sleep (Bonnet, Johnson, & Webb, 1978). Once an individual is asleep, the issues of whether he or she is a good or poor sleeper (i.e., awakens frequently) does not appear to be an important variable (Johnson, Church, Seales, & Rossiter, 1979).

Age is likely to be the next most critical variable, with major differences between the arousal thresholds of children, middle-aged adults, and elderly individuals. Older people are likely to awaken more easily than younger people, and children are generally the hardest to arouse (Busby, Mercier, & Pivik, 1994; Zepelin et al., 1984). Table 1 shows that arousal thresholds decrease from infancy to adulthood, with an average difference in waking threshold of some 44 dBA between children commencing school (5–7 years) and young adults (20–24 years). Clearly many children will not awaken to sounds that will awaken adults. The large standard deviations show the enormous individual variability that exists.

TABLE 1: Average Arousal Thresholds as a Function of Age

	N	Age (Years)	Average Threshold (dBA)	*SD*
Children	6	5–7	111.6	12.5
Preadolescents	10	8–12	101.5	18.9
Adolescents	10	13–16	97	21.1
Young adults	10	20–24	67.8	21.9

Note. Data from Busby et al., 1994.

Several factors may be operating that make it harder for children to wake up to sounds. Perhaps the most important is the hypothesis that children have higher electroencephalogram (EEG) energy levels (based on power spectrum density) within sleep, making arousal thresholds higher in all stages of their sleep as compared with those of adults. This hypothesis is based on extrapolations of adult EEG energy levels (across ages 18–43 years), which show a decline with advancing age (Astrom & Trjaborg, 1992).

Second, the duration of the deeper parts of sleep (especially Stage 4 sleep) declines with age, so that younger children spend more time in deep sleep than do older children and adults. In addition, the part of the brain that is responsible for making judgments (prefrontal lobe) is not well developed in prepubertal children, with most development occurring between the ages of 12 and 24 years. If the prefrontal lobe is responsible for making judgments while asleep (e.g., evaluating signals received) as well as while awake, then this may influence arousability.

The differential ability to be awoken in different sleep stages has received a lot of attention over the years. Stages 3 and 4 are subjectively the deepest part of sleep and predominate in the first third of a night of sleep. Most studies show (see Bonnett, 1982, and the Awakenings With Various Alarm Signals section) that it is harder to arouse a person from Stage 4 than from all other sleep stages and that arousal thresholds are approximately equal in Stage 2 and REM.

However, the average difference in decibel level needed to awaken an adult in different stages may be trivial. For example, Zepelin et al. (1984) found mean differences for nine 40- to 48-year-olds of only 6 dBA between REM and Stage 4 sleep, using a 5-s, 800-Hz tone. As noted earlier, such data would appear to be very susceptible to individual differences. Time of night differences, independent of sleep stage, do not appear to be robust (Bonnett, 1982).

Several studies have considered how sleep deprivation affects people's ability to respond to auditory signals when asleep. In some cases the experimental design relies on successful tone discrimination, or reaction time, rather than considering thresholds specifically. Performance is consistently reduced by sleep deprivation (Williams, Hammack, Daly, Dement, & Lubin, 1964), even after just one night of partial sleep restriction to 4 hr (Snyder & Scott, 1972). It is well known that sleep deprivation changes the architecture of sleep on the recovery nights, with considerably more Stage 4 sleep in the first third of the night. It also seems likely that EEG energy levels increase across all sleep stages in recovery sleep, presumably making it harder to arouse the sleeper.

Most early studies found no significant sex differences in arousal thresholds. However, there were some exceptions. Wilson and Zung (1966) found more responsiveness among sleeping women than men to sounds they were motivated (by a reward) to respond to, whereas Zepelin et al. (1984) found a trend for older women to have higher thresholds than older men.

The strongest evidence of a sex difference in arousability comes from the statistical modeling of arousal to low-level fire cues (Hasofer & Bruck, 2004). Involving a total of 53 adults and using four different fire cues (crackling sound, shuffling sound, flickering light, and smell), their study revealed a statistically significant difference, with women showing a higher probability than men of waking to each cue. A trend was also noted for the mean response time to awakening to be shorter for women. A subsequent study involving smoke alarm signals and alcohol consumption also found similar significant sex differences (see the subsection on impaired adults in the Awakenings With Various Alarm Signals section).

One study has considered the effect that a dose of hypnotics (flurazepam 30 mg) may exert on arousal to pure tones (Johnson et al., 1979). When the drug was exerting its maximum effect (some 2–3 hr after ingestion), the auditory threshold was approximately 30 dBA higher on drug nights than on placebo nights. There are no published studies available on arousal thresholds to sounds that are not alarms after consuming other drugs, such as alcohol or marijuana. Studies testing responsiveness to smoke alarms after intake of different soporific substances, including alcohol, are described in the next section.

AWAKENINGS WITH VARIOUS ALARM SIGNALS

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

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

Adults

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

Both studies clearly showed the detrimental effect of background noise (causing masking of the alarm signal) and suggested the importance of placing the smoke alarm within the bedroom itself to facilitate awakening. Masking will be further discussed in the subsection on Acoustical and Hardware Issues.

A decade later Bruck and Horasan (1995) exposed 24 young adults (18–24 years) twice to a 60-dBA alarm. The percentage who awoke to both alarm presentations varied slightly according to the sleep stage at the time of signal presentation, with 87%, 75%, and 75% awakening consistently across Stage 4, Stage 2, and REM sleep, respectively. Latency to awakening was longer in Stage 4 than in the other two stages (79 vs. 20 s or less).

It was found that those participants who slept through one or both signals were sleep deprived because of significant exam-pressure sleep restriction on the night before the experiment. Thus all the participants were not "unimpaired," and this introduced a confound into the study. Studies of adolescent and young adult sleep patterns (Carskadon, Harvey, & Dement, 1981) show that it is not at all unusual for individuals in this age group to have highly irregular sleep patterns, alternating nights of restricted sleep hours with nights of recovery sleep.

In a subsequent study, Bruck (1999) set out to more thoroughly investigate the waking likelihood of adults (across a wider age range) and children in the setting of their family home. A high-frequency beeping alarm was set up in the hallway of selected homes such that it reached the pillows of both parents and children at 60 dBA. The 16 parents involved were aged from 30 to 59 years, and the equipment was in their homes for five nights. Individuals who participated in the study were screened carefully and asked to abstain from any alcohol consumption and keep regular sleep/wake hours. They were told the smoke alarm would be activated on two of the five nights but did not know more specific details. It was always activated in the middle third of the night (1:00–4:30 a.m.). Impressively, all parents awoke on both nights within 32 s.

In a recent study (Ashley et al., 2005) 32 people with established normal hearing were tested in a sleep laboratory across the sleep stages of Stage 4, Stage 2, and REM. A high-frequency smoke alarm (3100 Hz) in the T-3 pattern was presented for 2 min at 75 dBA, and 96% of the participants awoke.

A large-scale study involving approximately 600 trainees sleeping at the Disaster Protection Center premises (Nakano & Hagiwara, 2000) found that 90% evacuated within 120 s. Of those who evacuated, 74% reportedly awoke to the 50- to 53-dBA hotel emergency bell, 9% awoke to the subsequent 60- to 67-dBA siren, 7% were awoken by others, 2% awoke to the final 48- to 55-dBA voice broadcast, and 8% were in an ‘other’ category. The degree to which these young men were unimpaired is hard to judge, as 193 reported that they had “drunk very much” during the evening and that 70 “got dead drunk.” Nevertheless, the reported rate of responding to the signals is high.

To date the only controlled studies of the response of sleeping adults to different alarm signals are by Ball and Bruck (2004a, 2004b). These studies adapted the method of limits procedure, whereby a continuous signal was presented via a bedside speaker, starting at the whisper volume of 35 dBA and increasing in 5-dBA steps to a maximum of 95 dBA. Signals at each volume were presented for 30 s and moved on to a higher volume if there was no response. Measured responses were both a waking EEG pattern and the pressing of a bedside button, and three signals were presented each night during Stage 4 sleep. The participants were self-reported deep sleepers aged 18 to 25 years, and a repeated measures design was used to minimize variability attributable to individual differences.

Their first study was a pilot study ($n = 8$) to determine the relative effectiveness of three newly developed signals in waking up participants. In the first section of this paper, the development of two signals presenting the naturalistic house fire sounds and the female actor’s voice (conveying emotion) was described (Phase 1 of Ball & Bruck, 2004b). The third signal tested in the pilot study (Phase 2) combined these two signals, continuously presenting each for 5 s (i.e., a signal shift). It was found that the female voice signal was significantly more effective than either the naturalistic house fire sounds or the signal shift in waking the participants up. The mean sound intensity required to induce EEG wakefulness with the female voice was 47.5 dBA.

In a further, similar study, the comparative effectiveness of the female voice (300–2500 Hz), high-pitch alarm (4000–5000 Hz), and a mixed-frequency T-3 alarm signal (500–2500 Hz, hereafter called the “mixed T-3”) were compared using 12 young adults (Ball & Bruck, 2004a). Based on the literature suggesting that signal significance was an important component in facilitating arousal, the researchers were expecting the human voice to be the most effective in waking participants up. However, it was found that both the female voice and the T-3 alarm were significantly more effective than the high-pitch alarm in awakening the participants at lower volumes. Figure 2 shows that the average sound volume required to awaken with the female voice and mixed T-3 was 59 dBA, compared with 72.5 dBA for the high-pitch signal (sober condition).

Children

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

Across several studies using a similar methodology, Bruck, Reid, Kouzma, and Ball (2004) found that significantly fewer children awoke to the high-frequency alarm than to two voice alarms or the mixed T-3 (see Table 2). The voice alarms consisted of either the child’s own mother’s voice (saying his or her name about once every 6 s) or a female actor’s voice (as used in Ball & Bruck, 2004a and 2004b). Table 2 shows that significantly more children awoke to both the voice alarms and mixed T-3 than to the high-pitch alarm. In addition, the children awoke more promptly to the voice alarm and mixed T-3 signal than to the high-pitch alarm, and this difference was also significant.

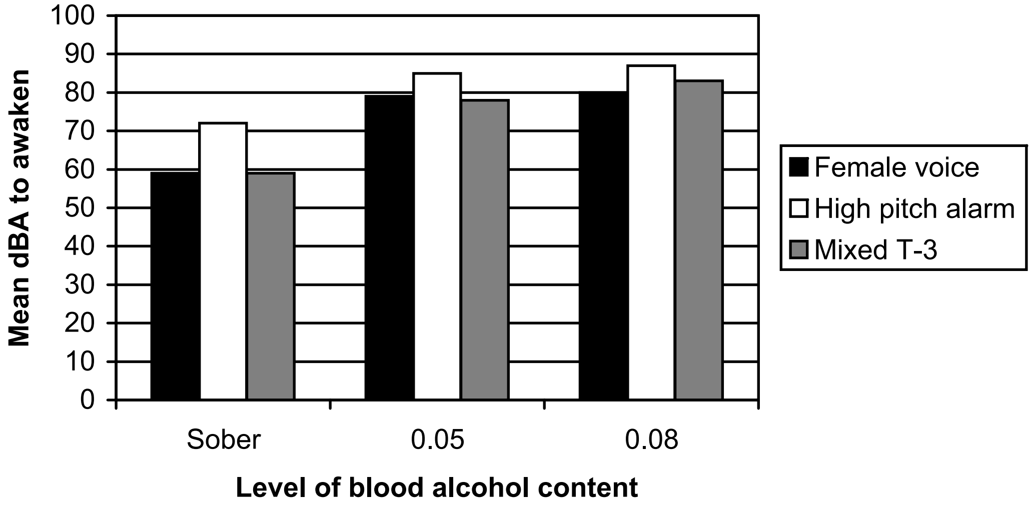

Figure 2. Comparison of the mean dBA levels of different alarms required to awaken young adults under different blood alcohol content conditions ($n = 12$). (Data from Ball & Bruck, 2004a.)

Impaired Adults

It is not surprising that the intake of hypnotics substantially reduces the ability to wake to a smoke alarm. Only one study has examined this effect experimentally (Johnson, Spinweber, Webb, & Muzet, 1987). It found that 50% of the adults receiving the hypnotic triazolam (0.25 or 0.5 mg) did not awaken to three 1-min, 78-dBA alarms presented during deep sleep, when the drug was exerting its maximum effect (2 hr postingestion); this is compared with the 100% who awoke with the placebo.

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

Figure 2 shows that responsiveness to both the female voice and the mixed T-3 were very closely matched, and both signals aroused individuals at a mean sound intensity that was lower than that of the high-pitched signal. It also shows the substantial increase in magnitude required for all signals when alcohol was administered. The research followed the modified method of limits procedure described previously, so the time taken from the first 30-s, 35-dBA signal presentation to when the participant responded with a button press was a key dependent variable. Analyses showed that the differences among the sounds and among the three alcohol conditions were statistically significant (MANOVA).

Further analyses of these data, applying a

TABLE 2: Number of Children Who Awoke Within Different Time Categories to Different Alarm Signals

	N	Valid[a] Alarm Presentations	0–30 s	31–60 s	60–180 s	Did Not Wake	% Total Awake
Mother's voice	20	19	15	4	0	0	100%
Female voice	20	19[b]	12	5	0	1	94.4%
High-pitch alarm	14	28[b]	10	1	4	12	57.1%
Mixed-frequency T-3	14	28[b]	14	7	0	1	96.4%

Note. Data from Bruck et al., 2004.

[a] The child reported retrospectively that he or she was asleep before the alarm was sounded. [b] In some cases the exact time taken to awake was not known, although the child awoke within 3 min.

sophisticated stochastic random walk model (Hasofer, Thomas, Bruck, & Ball, 2005), enabled predictions to be made about arousal, given a certain signal and certain individual characteristics. The modeling showed that both the estimated recognition probability and estimated waking up threshold of the various alarm signals is consistently different for women than for men, indicating greater sensitivity to the signal in sleeping women. As can be seen in Figure 3, alcohol clearly increases the threshold (statistically derived) for both sexes, resulting in an increased time to respond to the signals, which increased in volume every 30 s. As the curves are practically parallel, it is inferred that men and women not only have different thresholds when sober but are similarly affected by alcohol, albeit with a different level of sensitivity.

As auditory smoke alarms are by far the most commonly installed fire alarm and are compulsory in many countries, the issue arises of which type of signal is most likely to be heard by those with the most common types of hearing impairment. It is not simply a case of an increased volume being more effective. The most common type of hearing loss is that associated with advancing age, with U.S. census data (Lucas, Schiller, & Benson, 2004) suggesting that 14% of the population are hard of hearing. Considering only an older group, 46% of 48- to 92-year-olds (*n* = 3,753) were found to have some hearing loss (Cruickshanks et al., 1998), with older people most likely to lose their sensitivities to higher frequencies first. Figure 4 shows that hearing thresholds (when awake) for a tone at 3000 Hz are much higher than for a 500-Hz tone. Thus in order for a 70-year-old man to hear a 3000-Hz signal, it would need to be over 30 dBA louder than a 500-Hz signal.

In order to estimate the percentage of those aged 60 to 69 years who would not awaken to a hallway high-pitched alarm (55–60 dBA alarm of 2000–4000Hz), Bruck (2001) extrapolated from ISO 7029-1984 data (International Organisation for Standardisation, 1984) on hearing threshold values. Using a derived 41-dBA difference between awake and asleep thresholds, it was estimated that at least 25% of people in their 60s would not awaken to such a hallway alarm. Many people are not aware that their ability to hear high-pitched sounds is impaired with advancing age and assume that they will hear such a signal.

In a study testing the waking ability of the hard of hearing, 39 hearing-impaired individuals were exposed to an alarm during different stages of sleep

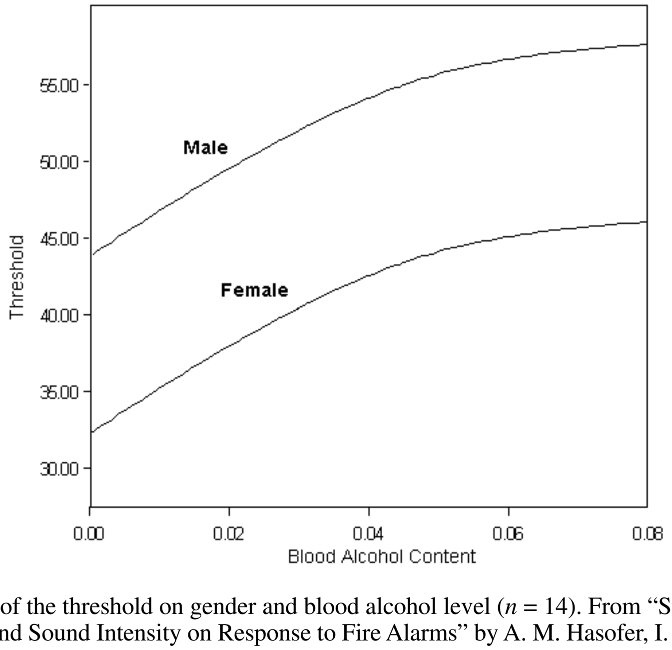

Figure 3. Dependence of the threshold on gender and blood alcohol level (*n* = 14). From “Statistical Modelling of the Effect of Alcohol and Sound Intensity on Response to Fire Alarms” by A. M. Hasofer, I. R. Thomas, D. Bruck, and M. Ball, in *Proceedings of the 8th International Symposium of the International Association for Fire Safety Science* (p. 515), 2005, London: International Association for Fire Safety Science. Copyright 2005 by the International Association for Fire Safety Science. Reprinted with permission.

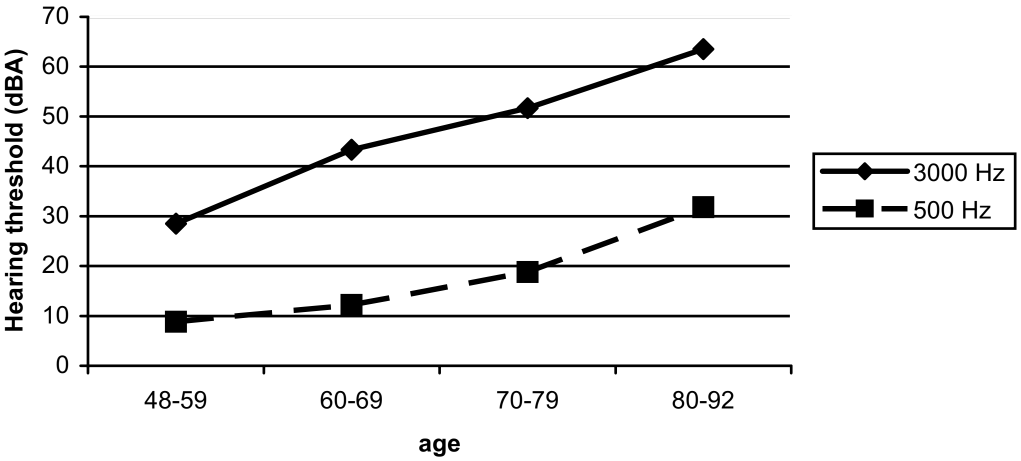

Figure 4. Hearing threshold values (dBA) for tones at two different frequencies for men of different ages (right ear) when awake. (Data from Cruickshanks et al., 1998.)

(Ashley et al., 2005). The hearing ability of these individuals was reduced by between 20 and 90 dBA over the frequency range of 250 to 8000 Hz. Across this group only 57% awoke to a 75-dBA, 3100-Hz signal.

Summary of Risk Factors

Studies on auditory arousal from sleep have shown that most unimpaired adults will awaken quickly to quite low volume noises, including hallway smoke alarms. One conclusion is that sleep in "normal" populations is not in itself the major risk factor for fire fatality but that additional risk factors need to be present to substantially increase the chance of not waking to an alarm. The literature from the studies of smoke alarms and sleep says that significant risk factors include being a child, being under the influence of hypnotics, being alcohol intoxicated, being hearing impaired, being aged over 60 (for high-frequency signals), being sleep deprived, and having high levels of background noise. Women tend to wake slightly more easily than men, but this difference appears to be subtle and overshadowed by the major individual differences in auditory thresholds.

It is not yet known whether there is consistency in which signal is most effective across different vulnerable populations. The research so far has found that the lower frequency signals were more effective for children, sober adults, and alcohol-intoxicated adults. What is not yet known is whether the best signal for these groups is also the best signal for those who are sleep deprived, are on hypnotics, or have age-related hearing loss.

ACOUSTICAL, METHODOLOGICAL, AND THEORETICAL IMPLICATIONS

Acoustical and Hardware Issues

The research suggests that the current high-pitched smoke alarm signal is less likely to awaken vulnerable individuals quickly than the alternatives tested. Contrary to earlier hypotheses, the critical factor is not the urgency or naturalistic nature of the message conveyed, the verbal content of a voice alarm, or the use of a voice in itself. The evidence from studies using young children, sober adults, and alcohol-intoxicated adults suggest that increased responsiveness is primarily a function of the lower frequency of a signal. Both a mixed T-3 beeping signal (500–2500 Hz) and the female voice alarm elicited a behavioral response in sober adults at around 13 dBA less volume than a high-pitched alarm (Ball & Bruck, 2004a). Similarly, the likelihood of a 6- to 10-year-old waking to a mixed T-3 or voice alarm is almost twice as great as awakening to a high-pitch alarm at the same loud volume (Bruck et al., 2004).

In order to be certain that the frequency of the signal is critical to waking effectiveness, further research is required comparing the efficacy of the same signal (e.g., the T-3) across a range of pitches. A key aim would be to more narrowly define the most effective frequency band. Those people representing hard-of-hearing individuals advocate a tone between 100 and 700 Hz (Mulvany, 2004). One study (Weir, 1976) considered the responsiveness of neonates to 75-dBA tones between 70 and 2000 Hz and found increased responsiveness at the lower frequencies (120–250 Hz).

It is possible that the critical optimal frequencies are those within the same pitch range as the human voice (less than 2500 Hz). The mixed T-3 tested (Ball & Bruck, 2004a; Bruck et al., 2004) was a complex sound with dominant frequencies across 500 to 2500 Hz, not unlike those of a voice. Complex sounds may have advantages over pure sounds in terms of the ability to be readily perceived and less likely to be masked. Patterson (1990) noted that for a signal to be reliably audible when one is awake, four or more of the spectral components of a warning should be at least 15 dB above auditory threshold. It would be interesting to compare responsiveness during sleep to complex signals of less than 2500 Hz (both voice and T-3) with responsiveness to a succession of three pure tones at three different frequencies of less than 2500 Hz.

The participant numbers in empirical sleep studies are often comparatively small and thus may hide important significant differences. A study with a larger sample would help determine whether the mixed T-3 signal and the female voice alarm are really equally effective. Similarly, the study with child participants suggested a marginal superiority for the mother's voice over a female actor's voice (Bruck et al., 2004), but a larger sample is needed to establish whether this is a significant difference.

The comparative effectiveness of alarms using a male voice versus a female voice also needs investigation. A female voice was chosen in these studies because of research showing that a female voice was perceived as more urgent than a male voice by individuals when awake (Hellier et al., 2002). However, urgency does not seem to be a critical factor in differential arousal from sleep, so extrapolations from the ergonomics literature on the effectiveness of signals when one is awake to when one is asleep may not be valid.

Research suggests that male and female voices activate distinct areas in the male brain, with the auditory cortex being more activated by female voices than male voices (Sokhi, Hunter, Wilkinson, & Woodruff, 2005). Sokhi et al. (2005) argued that this is compatible with the idea that female voices are acoustically more complex than male voices. On the other hand, if small variations in frequency are critical, the lower pitch of a male voice may be best. Comparisons of voice recordings of the same text by a male and a female actor suggested that the lowest dominant frequency of the male voice was around 200 Hz, compared with around 300 to 400 Hz for the female voice.

It is possible that the best signal may be one that incorporates a signal shift between a voice and a beeping signal. If so, how long should the signal shift be? The one study that has considered a signal shift found that a 5-s shift produced no advantage (Ball & Bruck, 2004b).

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

Several early studies considered the masking effects of background noise, (e.g., air conditioners) on the ability to wake up to the high-pitched alarm (see the subsection on adults in the Awakenings With Various Alarm Signals section). Clearly, the alarm signal needed to be louder to awaken the sleeper if significant background noises existed. Masking occurs when the presence of one sound inhibits the perception of another. Importantly, a signal with multiple spectral components is less likely to be masked than one with fewer spectral components.

The greatest masking occurs when two sounds are similar in frequency (Lawrence, 1970). If it is assumed that background noises in a bedroom tend to be low in frequency, a pure-tone low-frequency alarm signal would be at considerable risk of being masked by noises in the home. A study characterizing the spectral characteristics of the background noises in a range of "typical" bedrooms would be informative and relevant. When this information is put together with the information about which signal is most likely to awaken sleepers, the extent of possible masking can be determined.

If research determines that the most effective alarm for waking most people includes a low-frequency component (e.g., 500 Hz), then the challenge will be for the industry to create small alarms capable of producing such signals, whether they include a voice, beeps, or both. There is some concern that the production of low-frequency signals with sufficient power may not be possible for small alarms. This has been challenged (Schifiliti, 2005), with the claim that a manufacturer created "within a week" a small 24-DC voltage audible alarm with a 500-Hz component of 70 dB at 0.5 m (the current drawn was 110 mA, which included a strobe light).

In the light of this claim, it seems feasible that a small alarm could be created that includes low frequencies and also meets current specifications about sound intensity. This is likely to be much easier for a hard-wired AC alarm than for a battery-operated alarm, but the feasibility of the latter is yet to be thoroughly investigated. Given that microchips that record and play voices are now readily and cheaply available, alarms of sufficient intensity with a range of signals, including a voice, may be possible.

Earlier considerations of waking behavior and smoke alarms (Bruck, 2001) suggested that smoke alarms be placed in bedrooms such that the sound intensity at the pillow is as close as possible to 90 dBA. Furthermore, interlinking alarms between rooms (which is a requirement for new residences in some parts of the world) enhances the chances of early detection of a fire by a wider range of individuals within the house. These recommendations stand, no matter what the nature of the emitted alarm signal is.

Methodological Issues

One problem with the empirical research on smoke alarms and sleep is that all the participants have been primed to expect that a signal will go off on one of several nights. Priming will dramatically increase the chance of awakening to a signal (see the previous subsection on Signal Significance). One study with alarms attempted to control for this by having the participants be naive with respect to an alarm sounding (Bruck & Horasan, 1995). However, the authors concluded that the sleep laboratory environment had contaminated the sleeping participants' naïveté as to the first alarm signal because they interpreted all signals as significant, given the artificial nature of being wired up for a sleep recording in a laboratory.

Thus in all studies of the effectiveness of different smoke alarm signals to wake people up, the question of whether they would awaken as easily if they were not primed to the signal remains unanswered; it is not known whether the experimental findings are generalizable to people who have not been primed to expect a signal (i.e., who are sleeping in their homes, unaware of the likelihood of a fire). The research to date may be significantly overestimating the proportion of people who will wake up quickly to an alarm. Studies are needed in which there is a long time frame (e.g., 1 or 2 months) within which a test alarm may be activated. The difficulty is being able to do this under controlled conditions (e.g., alcohol intake, prior sleep deprivation, prior time in bed, sleep stage) and with accurate monitoring of the latency to awaken.

A related issue is that no published experimental studies involving sleep and arousal have considered signal detection theory as it relates to behavioral changes. This theory states that when awake, people not only are differentially sensitive to signals, they also set different criteria (or biases) for responding depending on the relative consequences of, for example, a false response (when there was no signal) versus a missed response. The setting of such a criterion or bias during sleep may occur and influence the likelihood of awakening. For example, will a parent awaken less easily to a smoke alarm if his or her child's bedroom contains fire sprinklers, as compared with if it contains no sprinklers?

Several studies have used the modified method of limits procedure to compare arousal thresholds to different stimuli (Ball & Bruck, 2004a, 2004b). Caution must be exercised in extrapolating the sound intensity thresholds determined under these conditions to thresholds that may be found if a signal at a single sound intensity level were presented. In the modified method of limits procedure, sounds at increasing decibel levels are present continuously, increasing by 5 dBA every 30 s. It is not known whether this continuity of sound would make the participant more or less likely to arouse at a given decibel level, as compared with a single presentation. The methodology is useful because it provides considerable sensitivity in determining comparative responsiveness to different signals.

As we discussed (see the Human Characteristics section), a feature of auditory arousal behavior is the enormous individual differences in thresholds. Thus if significant differences between signals are being sought, it is desirable either to use a repeated measures design or involve a large number of participants in a between-groups design. This is especially important if the size of the effect is likely to be small.

Theoretical Framework

The ability of alarm signals to arouse sleeping individuals has emerged as a considerably more complex matter than was once believed. Behavior in response to an audible emergency signal, whether activated when one is awake or asleep, can be thought of to occur via the following process:

Sensory processing (audible)
↓
Perceptual processing (recognizable, meaningful)
↓
Decision making (need to evacuate)
↓
Action (evacuate)

For a sleeping person, we assume that sensory processing can occur in the absence of waking up. Sound waves may be acting on the structures within the ear, but no conscious processing is occurring. Waking up occurs after sensory processing has successfully gone on to perceptual processing. After awakening, one's ability to make rational and effective decisions can be impaired by sleep inertia, especially in the first 3 min (Bruck & Pisani, 1999). The effect of sleep inertia on physical functioning with gross motor skills (i.e., the action of evacuating) has not yet been documented.

Whether or not perceptual processing occurs in a sleeping person exposed to an audible emergency signal is a function of individual factors and an interaction between signal and environmental factors. These have been previously discussed and can be described as follows:

- *Individual factors* include age, gender, sleep stage, sleep deprivation, blood alcohol content, use of hypnotics or other drugs, hearing ability, physical or intellectual disability, priming, and previous experience.
- *Signal factors* include sound intensity/volume in decibels; sound frequency/pitch in hertz; sound rhythmicity, relating to the duration of sound and silence as illustrated by the T-3 pattern; and signal type and significance (e.g., a beeping sound or a human voice).
- *Environmental factors* include the level of background noise, the type and configuration of furniture and soft furnishings, and placement of the alarm relative to the sleeping person.

All the studies reviewed in this paper considered variability in responsiveness at only the sensory processing level, given that all the participants had been primed to know exactly which signal to expect while they were asleep. There was no variability in perceptual processing because the participants had all been instructed to give a certain behavioral response when they heard a certain signal. In this context it is perhaps not surprising that no difference was found in responsiveness to signals as a function of their perceived significance (e.g., voice vs. T-3 beeps). The participants had been primed to perceive *all* of the presented signals as significant. Thus the research has effectively been testing which signal is most likely to initiate successful sensory processing.

Historical examination of international standards for smoke alarm notification reveals that sound intensity has been considered almost exclusively as an important variable. Over the past 11 years, standards around the world have been updated to include the T-3 pattern as the prototypical evacuation signal in fire alarms, in an effort to increase uniqueness and recognizability. With the introduction of the T-3 pattern, the aim was that the population would become educated to associate the T-3 with the need to evacuate because of fire. In other words, fire safety policy makers assumed education would facilitate the process from perceptual processing to decision making for responding to a smoke alarm.

As we discussed in the Signal Characteristics subsection, there is some evidence that this is not happening (Proulx & Laroche, 2003). For many sleepers it may be the case that any unexpected noise of sufficient volume will lead to perceptual processing; however, the ability to awaken to a given signal at a lower volume is expected to be enhanced with education (i.e., priming).

In determining the best emergency signal for waking sleepers, there are several tasks. The first is to determine which signal factors (in a typical bedroom environment) optimize sensory and perceptual processing (waking up) when sleepers, having different individual characteristics, have been primed. The second task is to determine which type of signal will most effectively facilitate both sensory processing and perceptual understanding (and thus waking up) when no priming has taken place. It is possible that a signal that is perceived as more significant (e.g., a voice) will be processed perceptually equally effectively under primed and unprimed conditions.

A further question arises as to whether perceptual processing will be equally well facilitated by the same signal among individuals with different characteristics. As discussed earlier, the research findings with different population groups comparing the waking effectiveness of signals with different frequency characteristics have yielded consistent results across children (aged 6–10 years) as well as across young adults under sober conditions, with 0.05% BAC, and with 0.08% BAC. This consistency across groups and conditions gives rise to the hypothesis that the results can be generalized to other groups who are "at risk" for sleeping through an alarm. However, it is possible that the situation is more complex than this and that different groups will respond better to certain signals than to other signals.

CONCLUSION

The research outlined in the current paper has stimulated a good deal of interest within the fire safety field. Several topics, such as the response of sleeping children to smoke alarm signals, have also generated publicity, which in turn has stimulated interest in the community at large. This research, particularly with populations shown to be vulnerable, has caused some people to reflect upon whether the smoke alarm they have in their home emits the optimal signal. However, small sample sizes in the relevant studies affect the strength and generalizability of results. Larger scale studies are needed to tease out the important issues that have emerged from the recent work – for example, the optimal pitch of the signal.

The challenge for those considering international standards for alarm notifications is to include design parameters that increase the number of people who will respond by attempting to account for individual differences. Selecting one alarm signal as the most effective may mean that not all situations or people will be covered. It is necessary to first gain a sophisticated understanding of all the relevant issues, based on rigorous research, so that when policy changes for the smoke alarm notification signals are made they are as applicable as possible across the population.

Obviously, signal standards cannot mandate for all factors present in all environments and all people, but standards committees should consider parameters that optimize the chance of the alarm being perceptually processed by as many sleepers as possible. As new technologies become available, new products are developed that aim to enhance responsiveness to smoke alarms in an emergency, including wireless solutions, bed shakers, and personalized signals. It is important that such new developments be well researched and that smoke alarms remain as inexpensive and as user friendly as possible.

There are still many unanswered questions about what type of emergency signal will be the best to awaken most individuals. However, if further research supports the current conclusions about the greater efficacy of lower frequencies, then published standards for emergency signals (such as the ISO 8201) should include relevant recommendations that can then be adopted by different regulatory bodies internationally. Given the enormous investment that has been made in smoke alarms in developed countries since the 1970s, it is important that the signal that people rely on to wake them if there is a fire is optimal. Evidence suggests that the current signal can be improved.

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Dorothy Bruck is a professor of psychology at Victoria University and a research associate of the university's Centre for Environmental Safety and Risk Engineering. She received her Ph.D. in sleep research from La Trobe University in 1991.

Michelle Ball is completing her Ph.D. through the School of Psychology and completing a coursework program in clinical neuropsychology at Victoria University, where she received a BA (Hons) with first-class honors in psychology in 2001.

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