ABSTRACT

Title of Document: WAKING EFFECTIVENESS OF EMERGENCY ALERTING DEVICES FOR THE HEARING ABLE, HARD OF HEARING, AND DEAF POPULATIONS

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The study presented measures the awakening effectiveness of a number of commercially available emergency alerting devices. Three groups of varying hearing levels were tested: hearing able, hard of hearing, and deaf. The devices evaluated are a typical audible smoke detector, a strobe light, and a bed shaker. The subjects were monitored for sleep stage during the single night tests and the emergency alerting devices were activated in Stage 2, Delta and REM stages of sleep.

Results indicate that the audible smoke detector was most effective for the hearing able population and least effective for the deaf population. The recommended alternative to the audible smoke detector, the strobe, was the least effective device when measured against the total United States population. The vibratory tactile devices were most effective across all hearing categories and sleep stage. When the tactile signal of the bed shaker was modified to vibrate intermittently, all persons were effectively aroused.

The research shows that the standard audible detector recommended for placement in all American homes is only effective in awakening those without hearing loss. The strobe is recommended by building and fire codes when hearing deficits are present but did not sufficiently awaken any population. Tactile devices can provide a sufficient means for awakening all populations regardless of hearing level, age or race.

KEYWORDS: Emergency notification, waking effectiveness, smoke detector, audible alarm, visual alarm, tactile alarm, hearing ability, hearing, hard of hearing, deaf, sleep, sleep stage.

WAKING EFFECTIVENESS OF EMERGENCY ALERTING DEVICES FOR THE HEARING ABLE, HARD OF HEARING, AND DEAF POPULATIONS

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

I dedicate this degree to my father, John Mack, who has taught me the true meaning of strength and resilience.

Acknowledgements

There is one person above all others who deserve my deepest thanks and respect for his continued support during the writing of this dissertation is my husband, Dr. Trevor Ashley. I could not have done it without his love, insight, and humor.

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I would like to recognize my parents, sister, brother-in-law, nieces and extended family that have been instrumental in my achievements.

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INTRODUCTION

In any given year, someone dies in a fire every two hours, and someone is injured in a fire every 29 minutes. Eighty percent of the fire deaths in the United States occur in the home, where smoke detectors are installed in 50% of such residences. Over three thousand people were killed in residential fires in the year 2003, and more than 14,000 were injured [Ahrens, 2003]. Fires and half of all fire deaths occur most often in the evening hours when the residents are asleep [CDC Fact 1, 2005]. However, the most effective mechanism for awakening the public to a fire emergency has never been fully verified.

The typical audible smoke detector may not awaken a substantial portion of the American public. It is estimated that 17% of Americans over the age of 18 (35 million people) have some form of hearing loss, and over 3% of those people are severely hearing impaired or profoundly deaf [Lucas, 2004]. More than 40 million Americans are hard of hearing and deaf and are at a disadvantage for receiving notification of a fire in their residence by the typical audible smoke detector.

Waking persons from sleep is of significant importance because the majority of fire deaths in residential settings occur between the sleeping hours of 11:00 pm and 6:00 am. Although only 20% of fires are reported to have taken place during this temporal window, nearly 50% of fire fatalities occur during this time [Ahrens, 2003].

Recent legislation, such as the Americans with Disabilities Act (ADA), has recognized the disadvantage that deaf and hard of hearing people have concerning notification by audible fire alarms [ADA, 1994]. As a result, many automatic fire detection systems are now required to signal with an audible alert accompanied by a strobe to provide a visual indication of fire alarm activation. Yet, the waking effectiveness of the strobe is unknown for the hard of hearing and deaf populations.

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Contribution

Research conducted by the Center for Fire Research at the National Institute of Standards and Technology (NIST) found that most deaf people are “fully capable of self-preservation if they are informed of the danger” [Levin, 1981]. However, the limitation for those with hearing loss is the inability of the typical audible smoke detector to adequately provide timely notification during the sleeping hours. This research will attempt to identify the waking effectiveness of several emergency notification devices available to the deaf and hard of hearing communities. The goal of this project is to provide a means for which persons with hearing loss can choose a device that will improve the chances for surviving a fire during sleeping hours.

The majority of U.S. homes are equipped with a typical audible smoke detector only. This detector sounds an alarm in the presence of smoke with a frequency range of 3000 to 4000 Hz. In some cases, the typical audible smoke detector is coupled with a strobe as a second means of alerting. This combination device is often marketed to the deaf and hard of hearing as a means for awakening where the typical audible smoke detector is not adequate. However, this combination device is often expensive and not equipped in the majority of homes leaving those in the hearing impaired community with a substantial disadvantage for adequate notification.

The NFPA 72 document, *The Fire Alarm Code*, recommends but does not require the use of the strobe in residences where those with hearing loss may live [NFPA 72, 2002]. The code states the following:

> *Since hearing deficits are often not apparent, the responsibility for this deficit shall be that of the hearing impaired party.*

Although the code recognizes that the hard of hearing and deaf communities are at risk in a fire emergency, little is written on the best mechanism to mitigate this risk. The lack of a relatively inexpensive device to provide deaf individuals access to notification of a fire seems unacceptable in light of current technology and the goals provided by the ADA and the National Fire Protection Association (NFPA).

The significance of this research is a function of the study's size, population, and rigor. There has been no other study on waking effectiveness of emergency alerting devices reported in the literature which utilized a population sample with three distinct hearing groups, ages of participants ranging from 18 years to over 90 years, and multiple emergency notification devices. Choosing a population sample with three distinct hearing levels provides an adequate representation of the true demographics of the United States in regard to hearing level. Since many of the emergency notification devices are based on one's ability to hear the tone, hearing level plays an important role in waking a person from sleep to an emergency notification device.

The age range of the subjects is also significant and unique due to the changes one experiences with age in their ability to perceive cues during sleep. Studies have been performed on the waking effectiveness of audible emergency notification devices on children, elderly and the adult populations. However, a single study comparing waking effectiveness of various age groups ranging from adolescence to elderly has not been performed.

Finally, the number of emergency notification devices utilized in this study exceeds other similar studies. Five devices were tested. Other studies indicated in the literature review section of this dissertation utilized only a single waking mechanism device (i.e., audible, visual, or tactile). The current studied looked at multiple audible devices, visual cues and two tactile devices.

As such, the current study is the most in depth analysis of waking effectiveness of emergency alerting devices available to date.

Goals

The research quantifies the waking probability of five emergency notification devices available to the general public and the deaf and hard of hearing community: the typical audible smoke detector, the strobe, the continuous bed shaker, the intermittent bed shaker, and the low frequency audible detector. The results indicate that the generally recommended devices were not successful in awakening the deaf, hard of hearing, and aged populations. It has been hypothesized and proven that alternative emergency notification devices can provide these risk groups with waking probabilities equal to the waking probability of the typical audible smoke detector for the average hearing able adult.

Limitations

The limitations of the study include sample size, age of participants, number of devices tested and the effect of long term hearing loss versus a gradual decline in hearing on the results.

This study included 111 adult subjects with a range of hearing levels. The risk groups of deaf, hard of hearing, and average hearing adults were targeted in the sample although each group is not mutually exclusive. The subjects ranged in age from 18 years to over 80 years of age; however, there was a heavy bias towards the college aged population (18-21 years of age). The bias is due to recruiting limitations and the prevalence of deaf college students in the local vicinity of the chosen sleep laboratory. Recruiting for the deaf and hard of hearing subjects focused heavily on the students of Gallaudet University, the world's only university for the deaf and hard of hearing. Gallaudet was chosen based on its proximity to NIH, the Sleep Services of America testing laboratory and this researcher. Children were not included in this study; however, recent literature indicates that children are a major risk group for not awakening to a typical audible smoke alarm signal [Bruck, 2000].

The elderly, independent of hearing level, have been introduced as a risk group for this study; however, difficultly recruiting this population resulted in a relatively small sample size. The subjects for this study were required not to be taking any medication that would influence their ability to perceive an alarm during sleep nor have any diagnosed sleep disorder. Sleep disorders include but are not limited to: insomnia (difficulty falling and staying asleep), sleep apnea (difficulty breathing during sleep) and/or narcolepsy (the irresistible need for sleep) [sleepnet, 2005]. Due to the decreased health of the average person over the age of 65, finding a large sample willing to participate without medicinal use or a diagnosed sleep disorder proved elusive.

Five devices were tested in this research: the strobe, the typical audible smoke detector, the low frequency smoke detector, and two tactile devices. These devices were chosen for inclusion in this study based on their prevalence of use and the results of research completed by other investigators. The choice to include such devices does not imply that other emergency notification devices on the market may not be beneficial in alerting the risk groups to an emergency event.

It has been theorized by this researcher, but unproven, that the propensity of the deaf subject to awaken to the strobe is due to a lifelong conditioning to such a device. Many of the emergency notification devices and non-emergency notification devices provided to the deaf community use a light source as an indicator of an ongoing event. Therefore, the deaf subjects may become sensitized to this type of indicator and may awaken to the light devices with a greater frequency than those without this lifelong sensitivity to light. It was unknown at the time of the testing which subjects had lifelong hearing loss, which could indicate a sensitivity to light, and which subjects have a gradual decrease in hearing leading to deafness. Conclusions cannot be made on how this limitation affected the results of this study.

Outline

This dissertation intends to evaluate the waking effectiveness of five devices for the deaf, hard of hearing, and hearing able populations. Background information is provided and will highlight the fire problem, the importance of such emergency notification devices and human behavior during an emergency event. Current research regarding waking effectiveness of emergency notification devices is discussed and will be critiqued to highlight the relevant information gained from each study. A detailed explanation on sleep is provided to aid the reader during the procedure and results section of this report.

The experimental procedure is provided in the third chapter. The procedure section includes the method for choosing subjects and a description of the emergency alerting devices used during the study. The methods for quantifying the device alerting mechanisms and the statistical methods used throughout the analysis are described in the experimental procedure chapter.

Results and discussion are provided in Chapters four and five, respectively. The results chapter intends to provide data and trends in the study data. Individual device data will be provided in the results chapter, as well as, specific data related to the deaf, hard of hearing, hearing able subject groups. A sample error assessment is provided in the procedure section of this dissertation. Finally, the weighted average effectiveness of each of the results will be analyzed and presented.

The discussion section aims to provide a detailed analysis of the results. Demographic significance will be addressed in relation to subject age, sex, and race. The effect of sleep stage on the results will be outlined and provided in this chapter. The results of the strobe effectiveness will be compared with relevant research. The mean response time to awaken will be addressed in the discussion section and the effect of awakening number on the results will be noted.

The final chapter will give a summary of the results, drawing conclusions from the research results presented in Chapter 4 and 5. A proof of hypothesis will be provided, as well as recommendations for further research.

BACKGROUND

Introduction

Notification of a fire is often marked by confusion, ambiguity or panic [Bryan, 1995]. Providing an alerting mechanism which alerts an occupant, relays pertinent information and allows to the occupant to begin the egress process has been the goal of most in the fire protection field. However, providing such an alerting mechanism that can appropriately alert all persons regardless of their state, level of awareness or alertness is difficult. The confusion that an occupant perceives might be compounded when the emergency alerting device is activated during sleep or when the cue is unfamiliar or unclear. This is compounded by the fact that the risk of fire and fire death increases in the evening hours.

The peak period for residential fires, based on data from the years 1994 to 1998, is between 6:00 PM and 7:00 PM, as shown in Figure 1 [Ahrens, 2003]. The trend has been suggested by Ahrens that this is due to family members returning home from work and turning up the heat or cooking their evening meal. Cooking and heating were the major cause of home fires during this same period. Home fire deaths peak in the early morning hours between the hours of 4 and 5:00 AM, even though the number of fires occurring during that time is the lowest for any given 24 hour period. Half of all fire deaths occur during the hours of 11:00 PM and 6:00 AM.

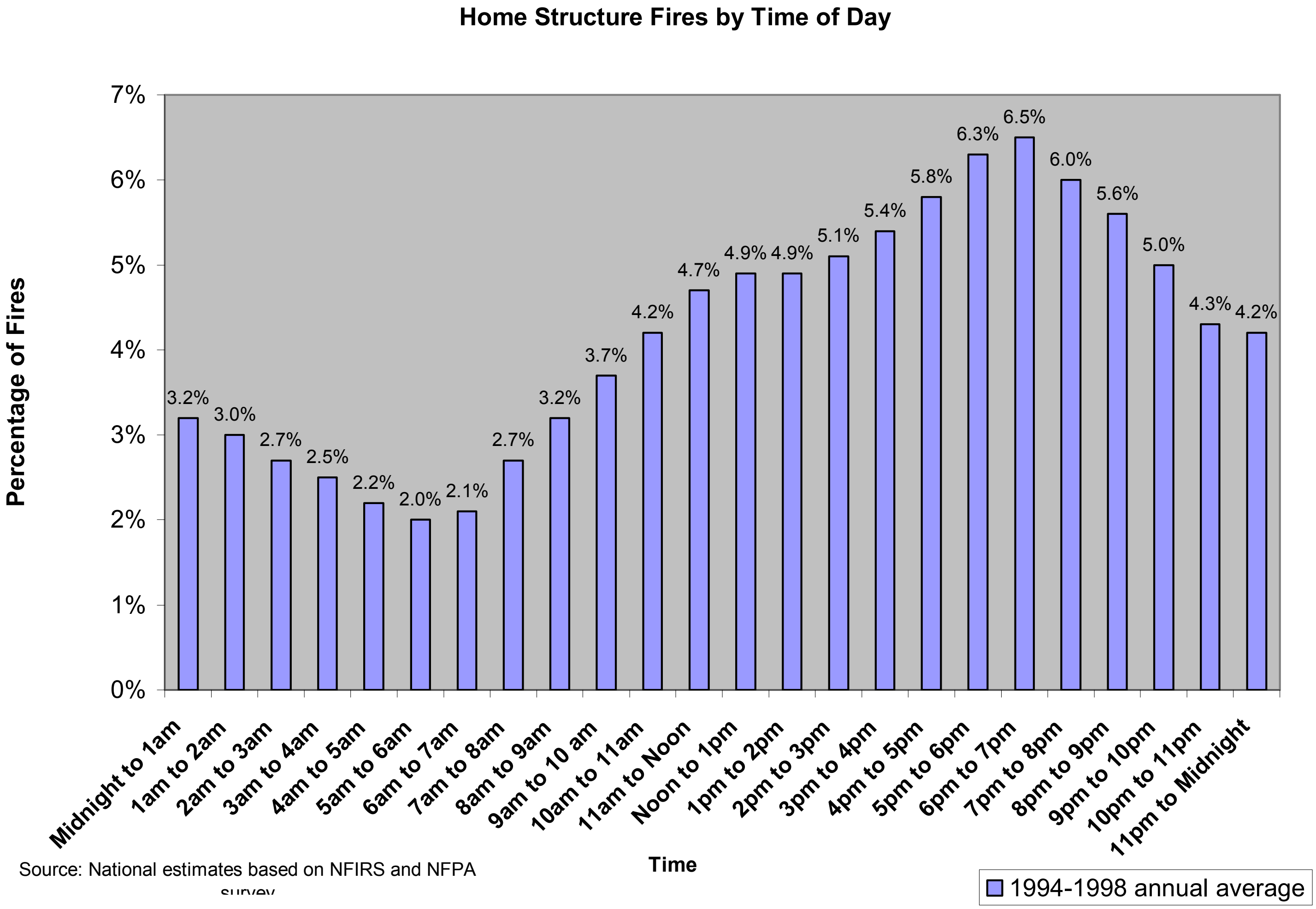

Figure 1. Home structure fires by time of day (Reproduced from Ahrens) [Ahrens, 2003]

NFPA 72, *National Fire Alarm Code*, recognizes the increased risk for fire and fire deaths in residential occupancies and specifically requires all residential homes to be installed with at least one audible smoke alarm. The smoke alarm sound intensity is based on the sound pressure perceived at the pillow location in a residential bedroom.

Therefore, the stringency of the requirements for the use of the audible smoke detector in a residential home is based on the use of this detector in the bedroom evening setting, the time at which being alerted to an emergency is most crucial [NFPA 72, 2002].

Typical audible smoke alarms were installed in approximately 95% of all residential spaces where a fire occurred per the National Fire Incident Reporting System (NFIRS), from 1995 through 1998. The use of smoke alarms in residential settings has grown dramatically since their introduction in the early 1970's. Figure 2 shows the dramatic increase in the use of the typical audible smoke alarm since 1970. Although the majority of homes in the United States are equipped with the typical audible smoke detector, the number of these alarms which remain functional after one year is only 20%. Where a fire occurred and was reported in the NFIRS database, approximately 65% of the smoke detectors were reported activated. The hypothesized reason behind the decrease in installed detectors and the activation of such detectors when needed might be due to the lack of operational batteries [Ahrens, 2003].

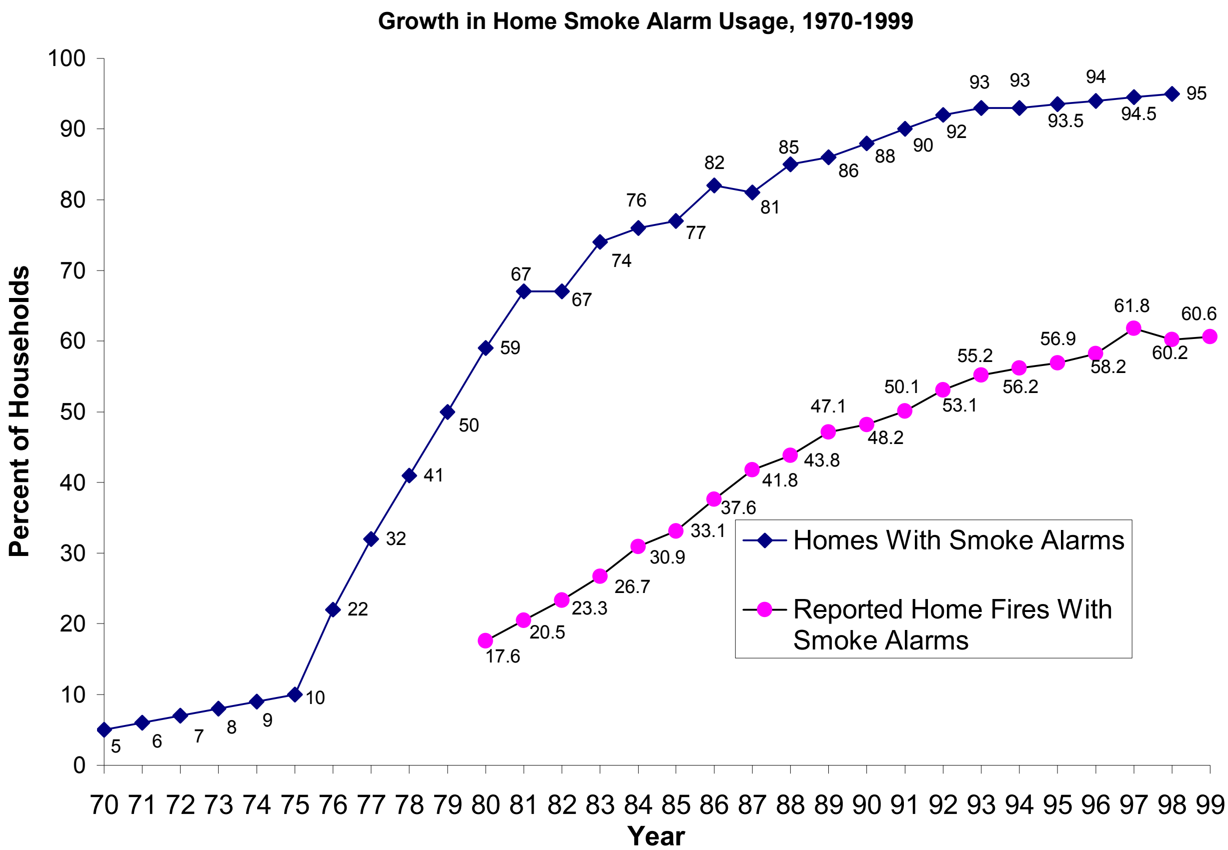

Figure 2. Increase in the use of the typical audible smoke detector (Reproduced from Ahrens) [Ahrens, 2003]

According to a recent publication by the Ahrens of the NFPA, the presence of the smoke detector in a home is congruent with a decrease in the risk of death due to a fire by 40-50% [Ahrens, 2003]. Per 1999 data, less than one (0.99) person died per 100 residential reported fires without a smoke detector and 0.51 deaths per 100 fires occurred in homes where a smoke detector is present. Although this data is compelling, a full correlation between the decreases in death rate in residential homes where smoke detectors are present has not been fully developed.

Risk Groups

The Centers for Disease Control (CDC) recognizes nine risk groups for fire safety: the visually impaired, the deaf and hard of hearing, college students, children, elderly, mobility impaired, manufactured housing residents, rural residents, and urban residents [CDC Fact 5, 2006]. For the purpose of this study, three such risk groups were identified and studied: the hearing impaired, children and the elderly.

It is estimated that 17% of Americans over the age of 18 (35 million people) have some form of hearing loss, and over 3% of those people are severely hearing impaired or profoundly deaf [Lucas, 2004]. This equates to more than 40 million Americans that are at a disadvantage for receiving notification of a fire in their residence by the typical audible smoke detector. An estimated 3% of the population is fully deaf, those without hearing 90 dB or less over the range of 500 Hz to 8000 Hz. Fourteen percent of the population is classified as hard of hearing. Hard of hearing is defined as those with hearing between 20 dB – 90 dB over the range of 250 Hz – 8000 Hz.

The hearing impaired population is at increased risk to not being warned, by the typical audible smoke detector, of a fire situation, therefore, limiting the time available to make safe egress. The deaf and hard of hearing cannot rely on hearing the traditional method for alerting persons to a fire, the typical audible smoke detector [CDC Fact 1, 2006]. Depending on the physical limitations of the individual, the hearing impaired might have to rely on another hearing able person to hear the alarm and notify them to the emergency. Although the deaf and hard of hearing have an increased risk of fire safety, the number of such people who have succumbed to fire or have been injured in a residential fire is unknown.

It is estimated that close to one thousand Americans over the age of 65 die in residential fires every year [Marshall, 1998]. Greater than 2400 Americans over the age of 65 are injured in residential fires every year. A recent study published in the Journal of the American Medical Association defined those over the age of 65 years as a "highly vulnerable group" to perishing in a fire. The presence of one risk factor, aged over 65 years, increases the fatality rate in a residential fire from 31% to 54%.

Twelve percent of the United States population is over the age of 65 years. This segment of the population is expected to nearly double to 20% or 71 million people by the year 2030. The baby boomer population, those born between 1946 and 1964, number approximately 30 million Americans and will turn 65 years of age starting in 2011. This group will experience a natural degradation of their hearing and will be at a disadvantage to hearing the higher frequency tones emitted by the audible smoke detector [Hobbs, 2001].

On average, approximately 800 children die in residential fires every year. More than 60% of these were children ages 4 and under. Approximately 40,000 children are injured every year in residential fires with more than half of these children being under the age of

4 years. The majority of all children who die in residential fires do so when they are sleeping [nclsafekids, 2005]. Dr. Bruck and others recognize that a disproportional number of children die in residential fires every year when compared to the general adult population [Bruck, 1999].

Children are recognized as a risk group. Several studies have been performed which address the waking effectiveness of emergency alerting devices. These studies have shown that the majority of children do not awaken to the typical audible smoke detector signal [1][Bruck, 1999].

Emergency Notification Devices

Emergency notification devices can notify the user to a dangerous situation through auditory, visual or tactile means. The most popular emergency notification device for the residential home is the typical audible smoke detector. This device was examined in its standard high frequency form, 4000 - 5000 Hz, and a lower frequency smoke detector, approximately 500 Hz. The strobe, a recommended alternative to the typical audible smoke detector, was also investigated. Additional tactile devices in the form of a bed shaker and an intermittent bed shaker were included in the study.

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[1] Although this group is at risk to not awakening to the standard emergency notification devices, children were not addressed in the present study. Adults who were capable of consenting for themselves were the only persons tested in study.

Typical audible smoke detector

The two main types of smoke detectors are ionization detectors and photoelectric detectors. Every residential smoke detector, regardless of type, must meet requirements set forth by the building or fire code adopted in the jurisdiction where the home is located. The major fire code addressing residential smoke detectors adopted by the majority of building codes is NFPA 72, *The Fire Alarm Code*.

The majority of the residential smoke alarms sold in the United States manufactured after 1996 adhere to NFPA 72 requirements for audibility. The standard for the temporal pattern, later adopted by ANSI S3.41 and ISO 8201, requires that the temporal pattern consist of three tones of ½ second separated by a ½ second with a 1 ½ second pause after the third tone [ANSI, 2005]. The signal may deviate from these times by up to 10%. The temporal three pattern is shown in Figure 3 [ISO, 1987].

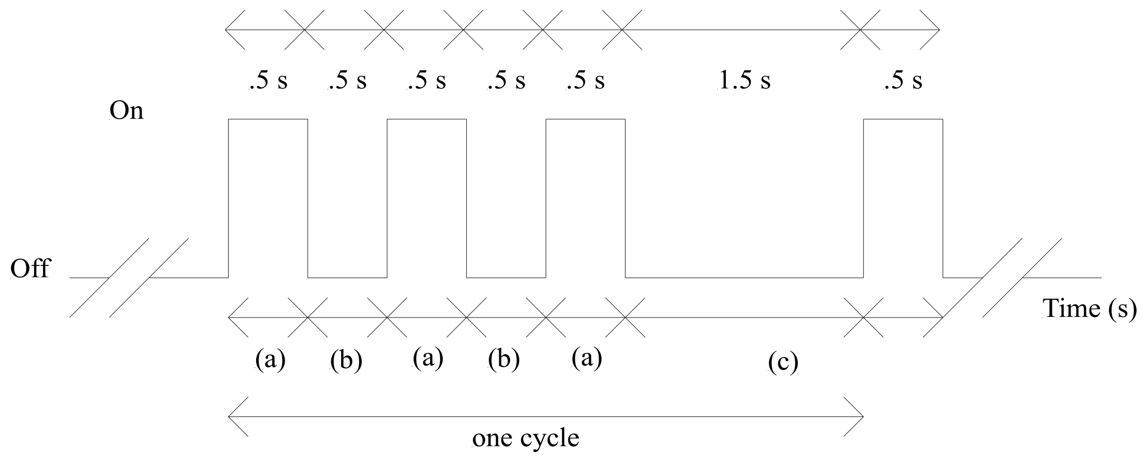

Figure 3. The temporal three pattern as defined by ISO 8201 and ANSI S3.41

The standard included in NFPA 72 states that the audible signal be no less than 75 dBA in sleeping areas. NFPA 72 includes a corollary suggestion wherein the power of the audible signal measure at least 10 dBA above ambient noise levels, except in sleeping areas where the signal should measure 15 dBA or above. The vast majority of residential smoke detectors on the market meet the requirements for sound pressure and pattern as defined by the NFPA 72 document.

Low Frequency Alarm

The typical audible alarm has frequencies in the range of 4000 -5000 Hz. Loss of hearing often occurs in the frequency range of the typical audible detector [Bonnet, 1982]. Loss of high frequency hearing with age, presbycusis, is not limited to frequencies in the 4000 - 5000 Hz range. Often, hearing loss can be found in frequencies below 500 Hz [Ross, 2003]. For those with hearing loss, the low frequency audible smoke detector can be a beneficial tool to alerting those persons to an emergency.

Few low frequency audible alarms are available to the general public. Power requirements of the low frequency detector often make the units expensive and difficult to acquire. The low frequency detectors that are available sound in the frequency range of 500 Hz to 2500 Hz. Often, the low frequency detectors alternate between the low frequency tone and a higher frequency tone.

Strobe

The strobe is a blinking light used to indicate an emergency. The light is triggered by a smoke detector, heat detector, sprinkler system or other fire sensing equipment. The strobe intensity can range from 60 candelas (cd) to greater than 177 cd. Although not required in residential homes by NFPA 72, the strobe is the recognized alternative to the typical audible detector for the hearing impaired. The Americans with Disability Act mandates that audible-alarm notification be supplemented by visible-alarm notification (such as strobe lights) to alert people with hearing disabilities [ADA, 1994].

Per NFPA 72 requirements, when the strobe is installed in sleeping areas, the strobe must meet an intensity of rating of 110 candelas when installed greater than 24 inches from the ceiling. When the strobe is installed less than 24 inches from the ceiling, it must have a visual intensity of 177 candelas [NFPA, 2002].

Tactile Devices

Tactile devices are used in the deaf and hard of hearing community as a method to initiate non-emergency awakening, similar to the audible clock alarm used by the hearing able community. The standard bed shaker alerts through a steady vibration and is placed under the mattress or pillow during sleep. The most readily available device to the general public is the bed shaker, a disc shaped device placed under the mattress. The tactile device is often hard wired to an alarm clock or smoke detector and vibrates when initiated by the alerting mechanism. Each tactile device varies in vibration intensity and frequency. A standard tactile device is shown in Figure 4.

Figure 4. Typical Bed Vibrator for non-emergency awakening

The tactile devices, although used as an emergency notification device, are not recognized by the major fire and building codes as a fire notification device. The systems are not approved or listed by any major testing laboratory, such as Underwriters Laboratory.

Human Behavior

Several factors affect how a person behaves in a residential fire. Human behavior can only be judged against the ability of the person to recognize the cues provided to them during the event [Bryan, 1994]. Cues can be categorized into three distinct groups: interpretation, preparation and action. Interpretation includes the receipt and the ability for the person to analyze the information provided to them. The emergency cue can be interpreted as a danger cue or misinterpreted as a non-emergency cue. When the cues are introduced during sleep, the interpretation of such cues becomes more complex. Recognition of fire cues is dependent on cue intensity, salience, focus of attention, and coherence (awake vs. unawake). Examples of cue intensity can be brightness, size, and potency. As one becomes more engrossed in a task, their focus of attention is diminished and the recognition of the cue can be decreased. Finally, whether a subject is asleep or awake can affect their coherence. As the subject falls deeper into sleep, their coherence decreases and their ability to react to an emergency cue is decreased [Khan, 1983].

Cue ambiguity is a major reason for misinterpretation of an emergency situation. Ambiguity increases reaction time, therefore, decreasing the time available for safe egress [Canter, 1990]. Ambiguity can be decreased if the subject's familiarity with the cue is increased. Therefore, whether a person is asleep or awake impacts the ability to perceive the cue as an emergency notification tool.

Sleep Stage

Sleep stage is believed to impact one's ability to transition from sleep to awakening. Rechtschaffen was one of the first researchers to introduce the idea that the deeper stages of sleep are more difficult to be aroused from [Rechtschaffen, 2000]. Therefore, it can be hypothesized that sleep stage will impact one's ability to awaken to the emergency alerting devices presented. For the purpose of this study, sleep stage is introduced and its impact on waking effectiveness addressed later in this document.

Three general measures are taken into account during a sleep study: gross brain wave activity, muscle tone and eye movement. The gross brain wave activity is measured by an electroencephalogram (EEG) and the muscle tone is measured by an electromyogram (EMG). The eye movement is recorded by an electrooculogram (EOG). The EEG reading is the most important measure in differentiating between the stages, while the EMG and EOG are most important in differentiating rapid eye movement (REM) sleep from the other stages [Hall, 2006].

Brain wave patterns can be classified into two types: beta and alpha. Beta waves are associated with wakefulness and are not consistent in pattern or appearance. The inconsistency in pattern is due to the day to day mental activity which consists of many cognitive, sensory, motor activities and experiences. During periods of relaxation, while still awake, brain waves become slower, increase in amplitude and become more synchronous. The alpha wave increases as the body relaxes.

Normal adult sleep is cyclic in nature and consists of five distinct phases: Stage 1, Stage 2, Stage 3 and 4 or Delta, and Stage 5 or REM. Stage 1 sleep is characterized by drowsiness and is the first stage of sleep in the sequence. During this initial 5 – 10 minute stage, the eyes are closed. The first stage of sleep is characterized by theta waves, which are even slower in frequency and greater in amplitude than alpha waves. The difference between relaxation and stage 1 sleep is gradual and subtle. In stage 2 sleep, the brain and body prepare to enter deep sleep. Muscles tense and relax, the heart rate slows, and the body temperature decreases. As the sleeper moves to stage 2 sleep theta wave activity continues, interspersed with two unusual wave phenomena. These phenomena, which occur periodically every minute or so, and are defining characteristics of stage 2 sleep, are termed sleep spindles and K complexes as shown in Figure 5. The former is a sudden increase in wave frequency, and the latter is a sudden increase in wave amplitude. If a person is awoken during one of these stages, he or she may report not being asleep at all.

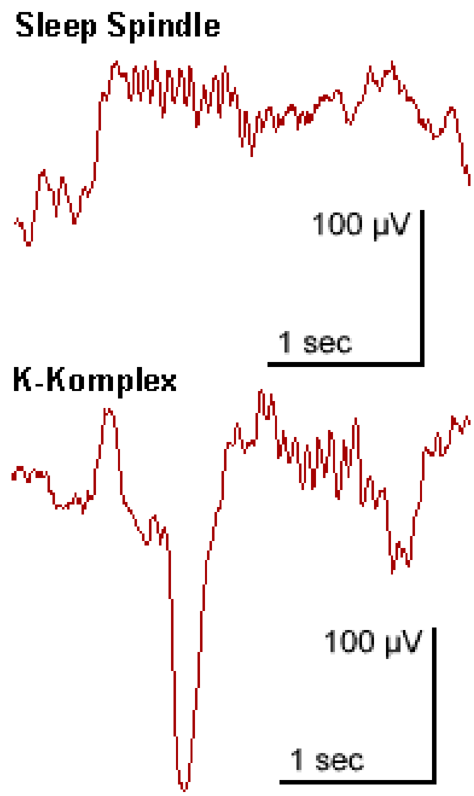

Figure 5. Comparison of the sleep spindles and K complex as defined in Stage 2 Sleep [Reproduced from Hall, 2006]

Stages 3 and 4 comprise the DELTA phase of sleep, the deepest sleep and, in theory, requiring the strongest stimuli to be awakened from. Brain activity slows during this phase. Stage 5 or REM sleep is unique in that the level of brain activity increases and is similar to stage 1. REM is an "active" sleep characterized by rapid eye movements. Heart rate and respiration speed up and become erratic, muscles twitch, but the body's major voluntary muscle groups remain paralyzed. As a person sleeps, he or she initially "descends" sequentially through stages 1 through 4, ascends sequentially through stages 4 to 2, and then enters REM sleep. The first occurrence of REM is 10 minutes in duration and occurs 90 minutes into the onset of sleep for most adults. From REM, the cycle of descending and ascending begins with stage 2 and continues with the depth of the cycle tending to become less with each sleep period. The REM sleep phase tends to reappear every 90 – 100 minutes throughout the sleep cycle and increases in duration with each period to a maximum duration of an hour. A comparison of the wave pattern for differing sleep patterns as measured by the EEG, EOG and EMG is shown in Figure 6 [Hall, 2006].

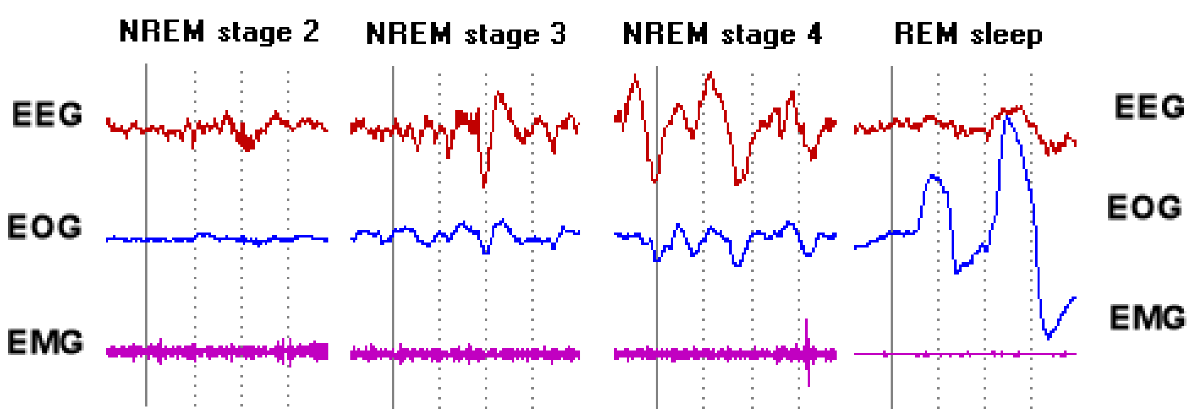

Figure 6. Typical sleep stages as measured by an EOG, EEG, and EMG [Reproduced from Hall, 2006]

The time the brain spends in each sleep phase is not equally distributed throughout the night. Stage 4 occurs predominantly during the first third of the night, while REM sleep is most prevalent during the last third. The distribution of sleep across each phase is also affected by age [Pezoldt, 1978]. On average, adult males spend less than 5% of their sleep in the Delta Stage of sleep, while men over 54 years of age spend less than 2% and young adult men spend greater than 20% of their time during sleep in the Delta stage. Therefore, as one ages, the amount of time spent in DELTA sleep decreases.

Arousal thresholds vary with the stages of sleep. [Bonnet, 1978]. Bonnet studied twenty-six young adult males with normal hearing. Each subject was exposed to a two second 1000 Hz tone in varying decibels. The arousal thresholds were determined to be 70 decibels above ambient noise (dBA) in stage 2, 92 dBA in stages 3 and 4, and 83 dBA in REM sleep. His second study found that subjects awoke one half of the time to 1000 Hz 75 dBA tones. The delta phase of sleep requires the most intense arousal and the arousal threshold differences between stages 1, 2 and REM are minimal.

For the elderly, the standard sleep cycle may not be typical. Several investigations into the sleep patterns of the elderly have been reported. Salzarulo, et al. examined twenty elderly subjects ranging in age from 65 to 75 years with a mean age of 69.3 years. All subjects were reported to be of normal health and were not prone to taking naps. Each subject spent a single night in a sleep laboratory where their sleep was recorded on a polygraph ERA using customary EEG tracking. The results of their study indicate that the mean total sleep time for the subjects was 318 minutes. One hundred and three spontaneous awakenings occurred with 20 being from stage one sleep, 55 from stage 2 sleep, 17 from stage 3 and 4 sleep and 11 from REM sleep. The results of the study indicate that the elderly subjects had a relative inability to maintain REM sleep due to disruptions in their sleep patterns. As discussed previously, REM sleep requires the least stimulation to awaken from, therefore, the elderly person not reaching the full REM sleep would be more difficult to arouse with the awakening mechanisms [Salzarulo, 1999].

Figure 7 shows the standard sleep patterns of the average 20 through 29 year old adult. For those between 20 and 29 years of age in the first three hours of sleep, the subject cycles through REM sleep and stage 4 in equal 1.5 hour intervals. After four hours of sleep, the 20 to 29 year old cycles between stage 3 sleep and REM. In the fifth through eight hour of sleep, the subject maintains REM sleep cycling with stage 1 sleep. During the early stages of the night, the subject maintains a heavy sleep pattern, making it more difficult to arouse. In the fifth hour of sleep, the 20 to 29 year old enters a lighter stage of sleep and in theory, would be easier to arouse [Grace, 1997].

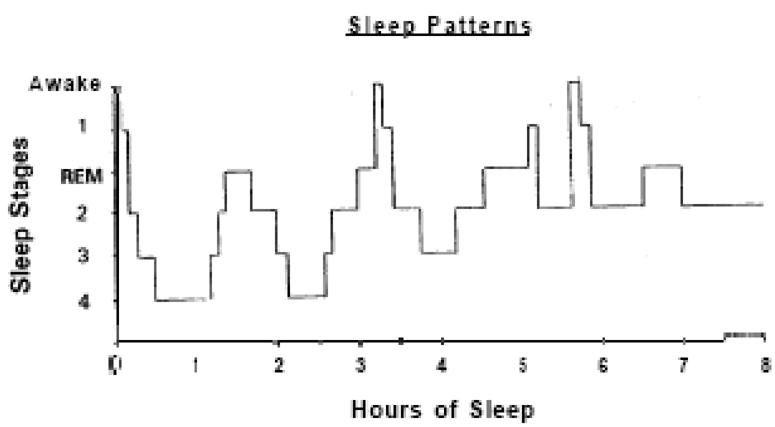

Figure 7. Sleep pattern for a 20-29 year old adult (reproduced from T. Grace)

Figure 8 shows the average sleep pattern of a nine year old child. The child maintains a cycle ranging from stage 1 sleep to the deepest stage four sleep during the first two hours of sleep. At the third hour of sleep, the child maintains a cycle of stage two through stage four sleep for the next two hours. After the fifth hour of sleep, the child's sleep pattern remains in the lighter REM and Stage two sleep. Into the seventh and eight hour of sleep, the child maintains a cycle of stage 1 and REM sleep. As with the adult, the child's sleep pattern remains cyclical with the deeper stages of sleep being had in the beginning the night. The child's sleep pattern maintains longer individual cycle lengths increasing in duration during the night. This pattern would indicate that the child is harder to arouse early in the night and would be easier to arouse as the night progresses.

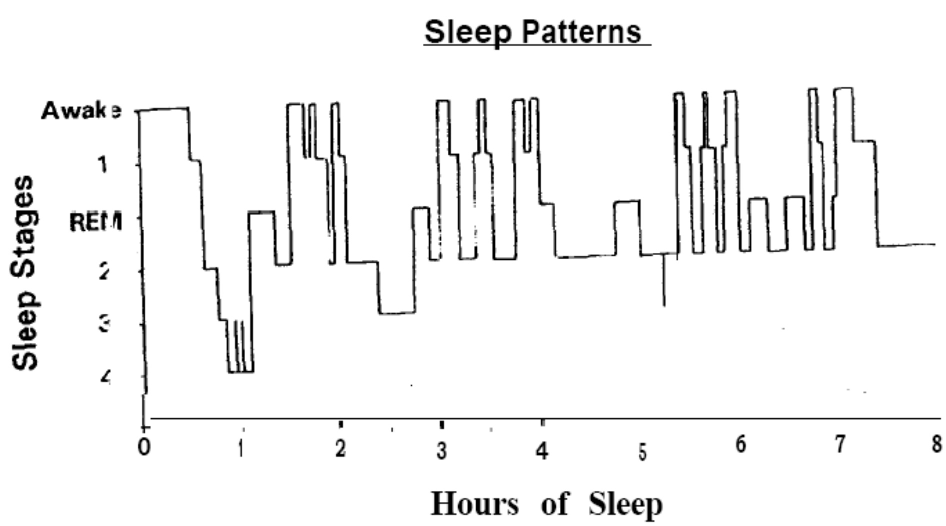

Figure 8. Sleep pattern for a 70 - 80 year old adult (reproduced from T. Grace)

Figure 9 shows the sleep pattern of the elderly aged 70 to 80 years old. This group is differentiated in their sleep patterns by the consistent waking and stage two cycles. The elderly adult often wakes in excess of ten times during a single night. The deepest sleep, Stage 4, is only entered once during a single night with the predominant sleep being had in Stage 2. It would be surmised from this figure and from relevant sleep research that the aged adult would be easier to awaken with notification devices. This, however, will be contested in the results and discussion section of this study [Boselli, 1998].

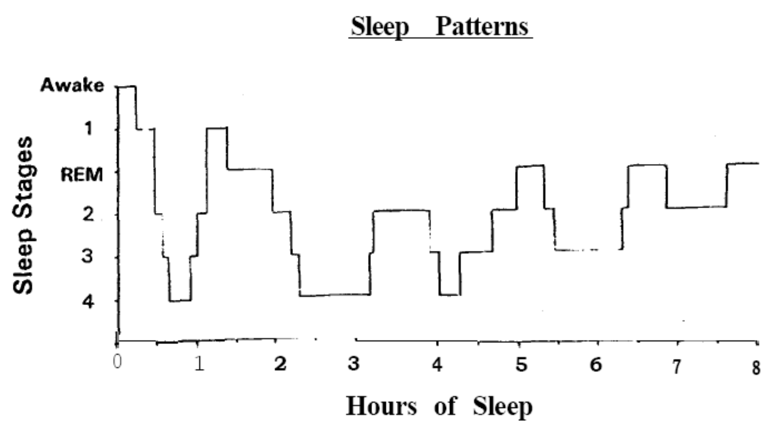

Figure 9. Sleep pattern for a 9 year old child (reproduced from T. Grace)

Literature Search

Audible Alarm Appliances

Dorothy Bruck of Victoria University in Australia has extensively studied the waking effectiveness of emergency alerting devices during sleep. Bruck and Horason in their paper entitled "Non-arousal and Non-action of Normal Sleepers in Response to a Smoke Detector," addressed how college aged students respond to the typical audible alarm during sleep. One unique aspect of this research is that the subjects were unaware of the true nature of the experiment; instead, each believed that they were participating in a study about dreaming. The smoke detector emitted a 60 dB sound in the frequency range of 2000 to 4000 Hz. Once activated, the alarm sounded for a maximum of ten minutes. If the subjects did not respond to the alarm, the sleep technician entered the test room and asked a series of questions to test their coherence. The subjects were told that they would be awakened once more during the night and that they were to press the intercom button next to the bed to communicate with the sleep technician [Bruck, 1995].

Of the twenty-four subjects studied by Bruck [Bruck, 1995], 80% were awakened by the smoke alarm sound. Bruck found no difference in the time of arousal between the tests where the subjects were aware that an alarm was sounded to awaken them and those tests where the subjects were unaware. Seventy-five percent of the awakenings occurred within 30 seconds of the alarm activation and 87% occurred within one minute. If the alarm did not wake the sleep test subject in one minute, the probability of awakening the subject dropped to less than 50%.

Khan performed a study which estimated the waking effectiveness of an audible alarm, heat and smoke odor [Khan, 1983]. The experiments were conducted on two groups of hearing able college-age male subjects. One group of subjects was tested with an audible detector with a volume of 75, 54, or 44 dBA. The second group was exposed to a smoke odor generated by the illumination of a spray painted light bulb, a separate heat presentation produced by the activation of a radiant heater, and a smoke detector presentation at 54 dBA. Khan did not assess the sleep stage of the subject during the study but activated the cue at distinct times: 2, 4, and 6 hours after the person initially fell asleep.

Khan found that 100% of the presentations of the 75 dBA smoke alarm, 42% of the 54 dBA smoke alarm presentations, and 25% of the 44 dBA smoke alarm presentations were detected by the first group of test subjects. In the second group, 58% of the 54 dBA smoke alarm presentations, 25% of the smoke presentations and heat presentations were detected by the test subjects.

Nober performed sleep tests to assess the alarm level needed to arouse subjects in their own residences [Nober, 1983]. Nober did not incorporate sleep stage in his tests but acknowledged the importance of sleep stage and influence it might have on arousal. Three separate sets of experiments were performed to assess the minimum arousal threshold for various alarms. The first set measured the intensity frequencies of several smoke alarm signals and arrived at a mean smoke detector sound power of 80 – 92 dB above ambient at 10 feet from the detector with frequency peaks between 3000-5000 Hz. The audibility of the smoke detector characteristic was found to drop to specific levels of 70 dB, or 55 dBA depending on the position of the detector inside or outside of a bedroom door.

The second set of experiments performed by Nober quantified the subjects' effective awakening to the mean detector signal against a number of variables: alarm sound level

(85, 70, and 55 dBA), background noise (63 dBA air conditioner), and hours into sleep, gender, and night of the week. The final experiments looked at the behavior of a designated respondent in his or her home and the time for the entire household to evacuate.

Nober found that college aged students aroused effectively to sounds greater than 55 dB above ambient. The subject had a greater chance of arousal if conditioned to the sound of the notification device prior to activation and sleep. For the tests performed in the individual residences, audible alarms were sufficient to awaken the majority of the test subjects and the egress time was less than two minutes for 75% of the subjects tested. The egress times for the elderly were found to be longer than the non-elderly due to mobility issues rather than difficulty awakening from sleep.

Overall, Nober, Bruck and Kahn found that for persons over the age of 18 and with normal hearing, the subjects woke to alarms most frequently with sound levels above 60 dB at pillow height. A comparison of the results of the mentioned studies can be viewed in Table 1.

Table 1. Waking effectiveness of typical audible smoke detectors for various alarm thresholds for hearing able college age subjects.

Researcher	Alarm Sound Pressure	Percentage of Subjects awakened
Bruck and Horason	60 dB at pillow	80%
Nober	55 dB above ambient	75%
Khan	75 dB	100%
Khan	54 dB	42%
Khan	44 dB	25%

Visual Alarm Appliances

Only two studies have been identified which address the waking effectiveness of visual emergency alerting stimulus: the UL 1971 report and a study by Bowman in 1995. Underwriters Laboratory (UL) studied the effectiveness of strobes for awakening the hearing impaired [UL, 1991]. The resulting report from this research has been instrumental in establishing the requirements for strobes in residences in the NFPA 72, *The Fire Alarm Code*, document. The report states that the 110-177 cd strobes in sleeping areas are equivalent in their awakening effectiveness to the typical audible smoke detector. The report examines the efficacy of strobes under different lighting conditions. In addition, the impact of a person's activity level in these environments on strobe alerting efficacy was also evaluated. The influence on air movement and vibratory stimuli on a person's ability to awake from sleep were also investigated.

UL performed tests to determine strobe-awakening intensities for sleeping deaf individuals during the night. One hundred and one individuals between the ages of 10 – 65 were tested in their homes. Multiple strobes with a variety of intensities were placed in the subject's bedroom at a height of seven feet located opposite the head of the bed. Volunteers were asked to write down the time of the strobe activation and if they were asleep during the activation of the cue. If the subject's reported time was within 4 minutes of the true activation time, the subject was said to have successfully awakened to the alarm. The test protocol indicated that volunteers were exposed to lights of decreasing intensity after positive tests for a maximum of four minutes duration between the time of 1:00 and 4:00 AM. Negative tests were repeated once at the same intensity and then resumed at higher intensities until successful results were again achieved.

Overall, 88% of all of the study participants, including those using medication, were able to perceive the 110 cd strobe. If the subject admitted to taking medication during the test night, their chance to awaken dropped to less than 30%. Younger un-medicated volunteers were less likely to perceive the alarm while asleep: children aged 14 to 18 awoke 91% of the time to the 110 cd strobe, while those under 14 years of age awoke 86% of the time. Of the 22 adult subjects not taking medications, 100% awoke to 110 cd strobes while 95% were awakened to 40 cd strobes.

A second study by Bowman tested the waking effectiveness of strobes for twenty-seven persons of normal hearing [Bowman, 1997]. The strobes met or exceeded the recommendations set forth by ADA, 177 cd. The results of the study indicated that only one of the twelve persons tested in slow wave sleep awoke to the strobe within five minutes of activation [Bowman, 1995]. Eleven of the fifteen persons were awakened by the strobe during REM sleep. Overall, only 44% of the subjects were aroused by the visual signals. Several studies are presented in the literature which suggest that light is an effective mechanism for awakening subjects [Tsuji, 2003]. However, the studies utilized ambient light with intensities much lower than the standard visual emergency alerting devices [Vasquez, 1998].

Tactile Devices

UL investigated vibratory stimuli on test subjects sleeping in their own residences. The vibratory device operating at 100 Hz was placed either under the subject's pillow or centered under the mattress. Volunteers responded 90% of the time to the pillow shaker and 84% of the time to the mattress shaker [UL, 1991].

Recent research by Combustion Science and Engineering, Inc. (CSE) has shown the effectiveness of the vibratory devices in awakening sleeping subjects. CSE performed a series of sleep tests on mainly college aged subjects to determine the effectiveness of a vibrating device to awaken a deaf individual. A vibrating watch, pager, pillow and bed shaker was used in their study. Qualitatively, from lowest to highest, the vibration intensity of the vibrating devices was as follows: watch, pager, variable bed vibrator, and super-shaker bed vibrator [Roby, 2005].

The sample consisted of six individuals with life long hearing loss classified as fully deaf. The subjects were aroused a maximum of three times throughout the night, allowing for a total of 18 arousals. The subjects were outfitted with multiple devices to ensure successful awakening, although, only a single device was activated at a time.

From CSE's final report, their results indicate that eighty-seven percent of the subjects in Delta sleep were awakened by a tactile device. Stage 2 sleep usually occupies 45-60% of an adult's sleep time, and 100% of the subjects were awakened during this stage of sleep. The arousal success rate was 71% for subjects in Stage 5 sleep, also known as rapid eye movement (REM) sleep, which occupies 20-25% of an individual's sleep time [Akerstedt, 2002]. Table 2 details the success rate for awakening subjects in various stages of sleep.

Table 2. Success rates for arousing deaf subjects from various stages of sleep.

Sleep Stage	Positive Responses	Total Attempts	Success Rate
Delta	6	7	86%
REM	5	7	71%
Stage 2	3	3	100%

The vibrating watch failed to awaken any sleeping subjects; however, per the CSE final report it was not clear to the researchers whether the watch was truly activated during the test. The pager awakened the test subjects from sleep approximately 30% of the time. The bed shaker, which was placed under the mattress, was successful in awakening the sleeping individuals 77% of the time. Table 3 details the success rate for the various devices used in these tests [Roby, 2005].

Table 3. Success rate of various devices for arousing deaf subjects from sleep [Roby, 2005]

Device Tested	Positive Responses	Total Attempts	Success Rate
Watch	0	3	0
Pager	4	13	31%
Variable Shaker	10	13	77%

Currently, research is being undertaken by the Fire Protection Research Foundation to assess the waking effectiveness of alarms for the hard of hearing and the elderly. Four alarm signals were tested on subjects ranging in age from 65 to 85 years. A high frequency T-3 patterned audible detector with a 3000 Hz signal was tested to represent the typical smoke alarm sold in the United States [Bruck, 2006]. The three additional devices investigated in this study included a 500 Hz T-3 patterned smoke detector, a mixed frequency T-3 patterned smoke detector with harmonics between 520 Hz and 2700 Hz, and a male voice with a frequency between 200 and 2500 Hz.

The subjects were determined to be independently mobile and were not taking medication that would affect their sleep. The hearing of all participants was tested and deemed "normal" for their age. The study was conducted in the home of the participant over a two night period during Stage 3 sleep. The subjects were monitored with an EEG system with two signals presented each night. The alarms were presented with an intensity of 35 dBA and increased by 5 dBA until the subject was awakened and pressed a button on a bedside table. Two key variables were investigated: the auditory threshold required to awaken the test subjects and the behavioral response time, the time between signal activation and when the subject pressed the bedside button.

The preliminary conclusions from Bruck's study indicate that older adults needed a lower volume to wake to the mixed T-3 than the other devices tested. The typical smoke detector signal, the high frequency T-3, was the worst performer of the signals and needed the highest volume to awaken the subjects. The voice alarm was deemed not suitable for waking the older population. The key recommendation from the study was the high frequency typical smoke detector sold in the United States should be replaced by an alternative signal that performs better in waking the elderly.

PROCEDURE

Introduction

The purpose of this study was to investigate the waking effectiveness of various alerting devices for the deaf and hard of hearing. Previous researches by Combustion Science & Engineering and Underwriters Laboratory (UL) have examined alternative means of awakening individuals beyond the typical audible smoke detector and the strobe. Such devices include tactile devices and low frequency alarms in the frequency range of 400 to 500 Hz.

Work by Underwriters Laboratory and Combustion Science and Engineering (CSE) showed that the use of tactile devices can be an effective method for awakening all subjects regardless of hearing level. CSE showed that vibratory devices held under the bed were more effective than using a vibratory device physically attached to the body, as in a watch style tactile device. Work performed by Dorothy Bruck indicated lower frequency alarms may be beneficial in awakening children and those with high frequency hearing loss [Bruck, 2003]. Based on the results of the studies by Bruck, CSE and UL, it was hypothesized that the use of a tactile device placed under the mattress or a low frequency alarm may be beneficial in awakening the hearing impaired.

To better understand the waking effectiveness of any device proposed for the deaf, the effectiveness of the standard smoke detector had to be ascertained for the hearing able population. Thus, the test population had to incorporate both deaf, hard of hearing, and fully hearing able people. Each subject was attempted to be awakened in one of three sleep stages: Delta, REM and S2.

Subjects

The initial recruitment goal was to test 120 people: 40 deaf, 40 hearing able, and 40 hard of hearing. Sample sizes of 40 are consistent with a binomial distribution with previous success rates near or greater than 80% and a sample error less than 10%. The success rates were ascertained from previous work performed by Combustion Science and Engineering, Bruck, and UL. The subject population attempted to replicate the demographics of the Unties States in relation to sex and ethnicity as shown in Figure 10 [US Dept. of Commerce, 2000]. Fifty percent of the subject population was to be male, and 50% was to be female.

The sample was chosen as a probability sample using the method of judgment-stratified sampling. Sampling methods can be classified as either probability or non-probability. In a probability sample, each member of the population has a non-zero chance of being selected. Therefore, any member of the population may be called to serve as a sample population. In a non-probability sample, the degree to which the sample differs from the population is not known. Due to time and financial constraints, a true probability sample could not be attained for this study.

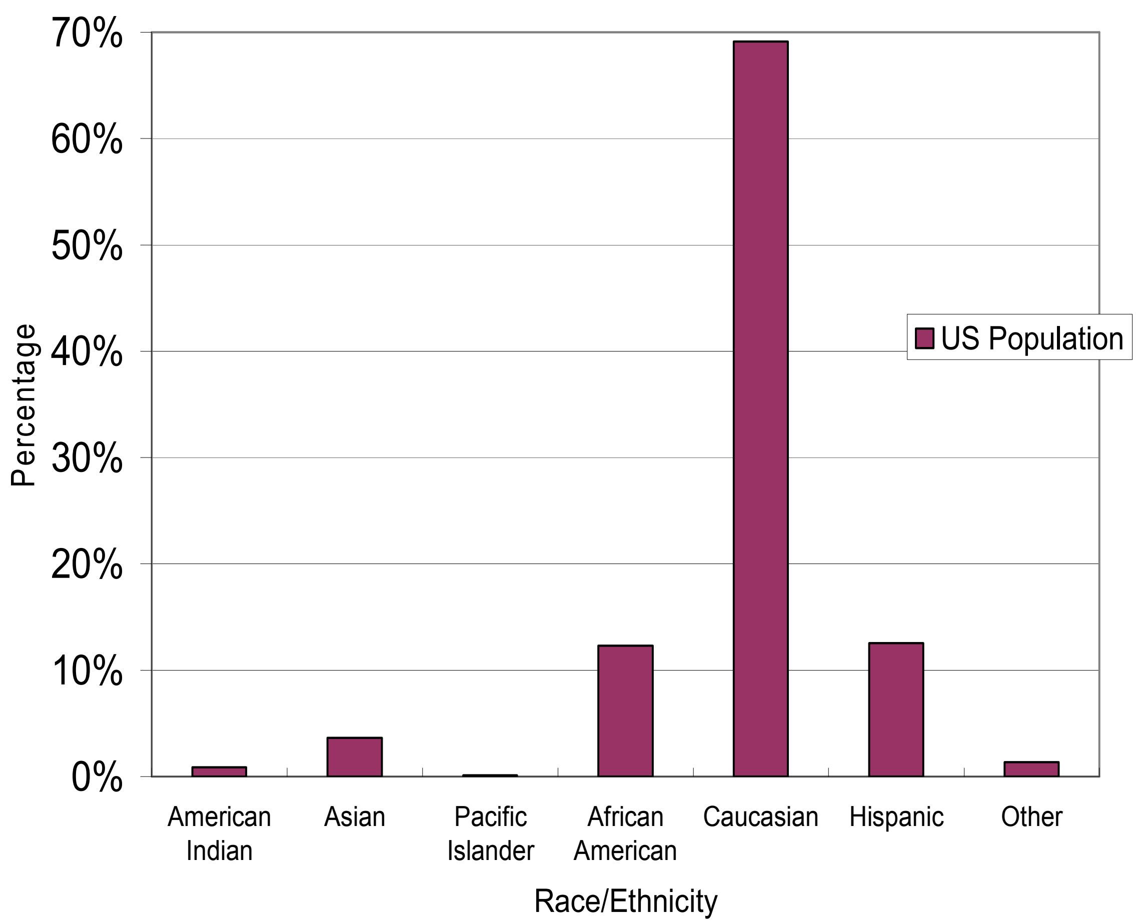

Figure 10. Ethnic background of the United States and attempted sample demographic [US Dept. of Commerce, 2000]

Each applicant was asked to fill out a pre-trial questionnaire to indicate his or her name, contact information, race, age, hearing ability as he or she perceived it, and the manner in which he or she typically was awakened to emergency and non-emergency events. Each person accepted into the study was given a hearing test for the conduction of pure tones through both air and bone to validate the subjects' assessment of his or her hearing. The medical consultant on this project, Dr. John Biedlingmaier of the University of Maryland Medical Center, interpreted the audiograms for each volunteer to assess into which hearing category the subject should be placed.

Deaf subjects were defined as those with no hearing 90 dB or less over the range of 500 Hz to 8000 Hz. Fully hearing individuals had hearing of 20 dB or less across the frequency spectrum of 250-8000 Hz. Participants were classified as hard of hearing if their average hearing ability fell between 20 dB – 90 dB over the range of 250 Hz – 8000 Hz.

Human Subject Testing

This research involved the use of 111 human test subjects. The research was submitted and approved by the Chesapeake Research Review, Inc.'s Institutional Review Board (IRB).

Emergency Alerting Devices

Five devices were chosen for testing in this study: the standard audible smoke detector, the strobe, the low frequency audible detector, a continuous bed shaker, and an intermittent bed shaker.

The audible detector chosen was a Firex Model CC smoke detector. The audible detector's sound pressure was adjusted so that the alarm sounded at 81 ± 4 dB at pillow height. The audible smoke detector was placed within the sleeping room during all tests and a sound pressure value was measured prior to the test. From NFPA 72, the requirements for sleeping rooms are as follows:

> *Where audible appliances are installed to provide signals for sleeping areas, they shall have a sound level of at least 15 dB above the average ambient sound level or 5 dB above the maximum sound level having a duration of at least 60 seconds or a sound level of at least 75 dB, whichever is greater, measured at the pillow level in the occupiable area, using the A-weighted scale (dBA) [NFPA 72, 2002].*

The 75 – 85 dB at pillow height range for the typical audible smoke detector was deemed appropriate [NFPA, 2002]. Previous research by Khan demonstrated that close to 100% of the hearing able would awaken to such a 75 dB alarm [Khan, 1983]. Ambient noise at the testing facilities measured between 25 and 45 dB. Thus, the 81 dBA rating exceeded both the 75 dB requirement and the 15 dB above ambient requirements of NFPA 72.

A second smoke detector, the low frequency detector, operated in the frequency range of 400 – 500 Hz. The alarm chosen was a modified "Loudenlow" manufactured by Darrow Company. This detector was introduced later in the test set due to the difficulty in locating a low frequency detector; therefore, a relatively small test sample was acquired.

This device was introduced to determine whether a detector with a lower frequency would awaken those with hearing loss in the upper frequency spectrum. The detector maintained an 80 dB sound pressure at pillow height as measured by the sound pressure monitor. However, it is unclear how the lower frequency of the detector affected the sound pressure results. The sound pressure level has the advantage of being an objective measure of sound intensity, but it may not be a true measure of what is actually perceived by the human subject. The sound pressure does not take into account frequency of the sound, where the ear's sensitivity is strongly dependent on frequency [Gunn, 2005].

The 1 Hz VA3 "Firewall M series" strobe was utilized in this study. The "Firewall M series" is manufactured by SAE and rated at 110 cd. The strobe was placed approximately 2 feet below the ceiling during all tests. The placement of the strobe was chosen based on the requirements set forth by NFPA 72. NFPA 72 requires that for sleeping areas, the strobe maintain a 177 candela light intensity when placed less than 24 inches from the ceiling and a 110 candela light intensity when placed greater than 24 inches from the ceiling. A light meter was used to quantify the effect of distance on luminosity, as shown in Figure 11.

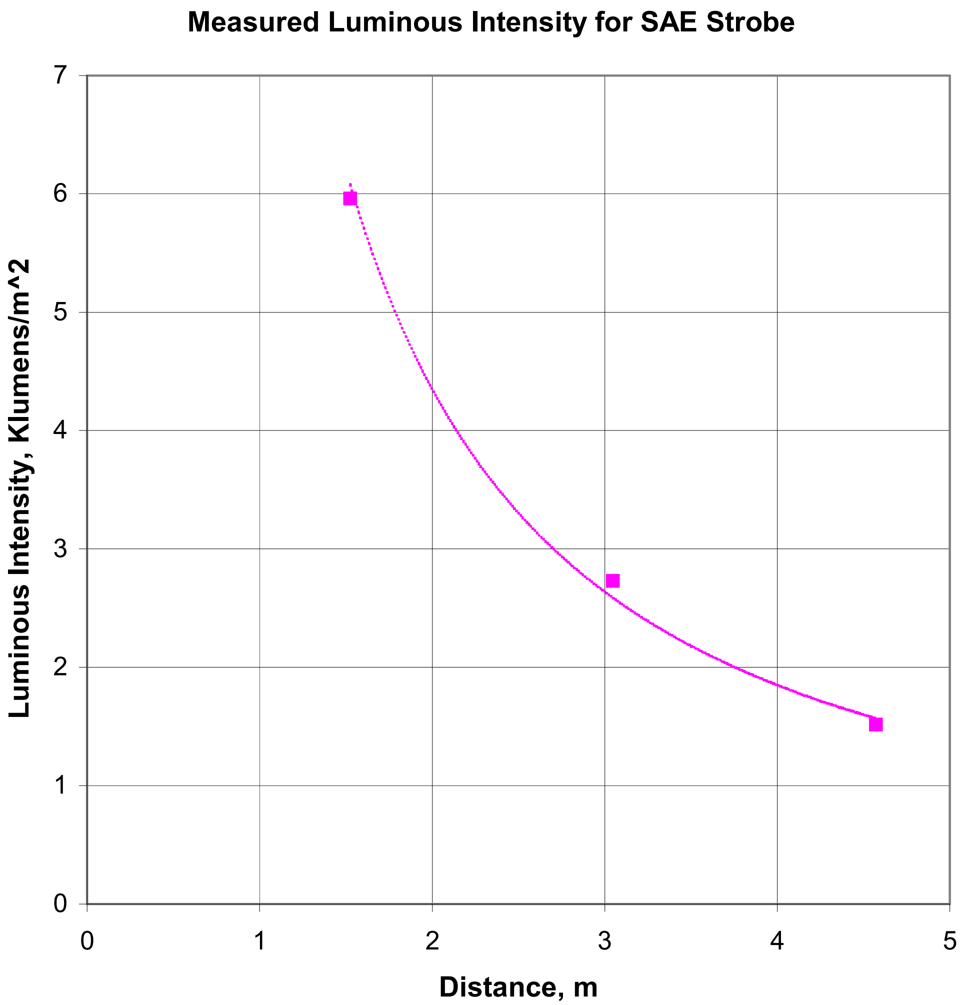

Figure 11. Luminous intensity characteristic for SAE 110 cd strobe [Roby, 2005]

A SonicAlert© Super Shaker Bed Vibrator, the continuous bed shaker, was utilized for this study. The continuous bed shaker was placed between the mattress and box spring in middle of the queen size bed in the laboratory. An accelerometer was used to quantify the intensity of the vibration on the test laboratory beds prior to each test with the bed shaker activating. A 3-axis accelerometer was used to quantify the intensity of the vibration felt by a subject in the bed. Due to the subject lying in the bed, the compression caused by this person would alter how the vibration is transferred through the mattress. To replicate the subject lying in bed, a 10 lb. mass was attached to the accelerometer. The 10 lb mass was chosen to replicate the weight of an average person's head as described in literature [Page, 2001]. The root sum of each axis of acceleration squared (RSS) is shown in Figure 12 for the continuous bed shaker.

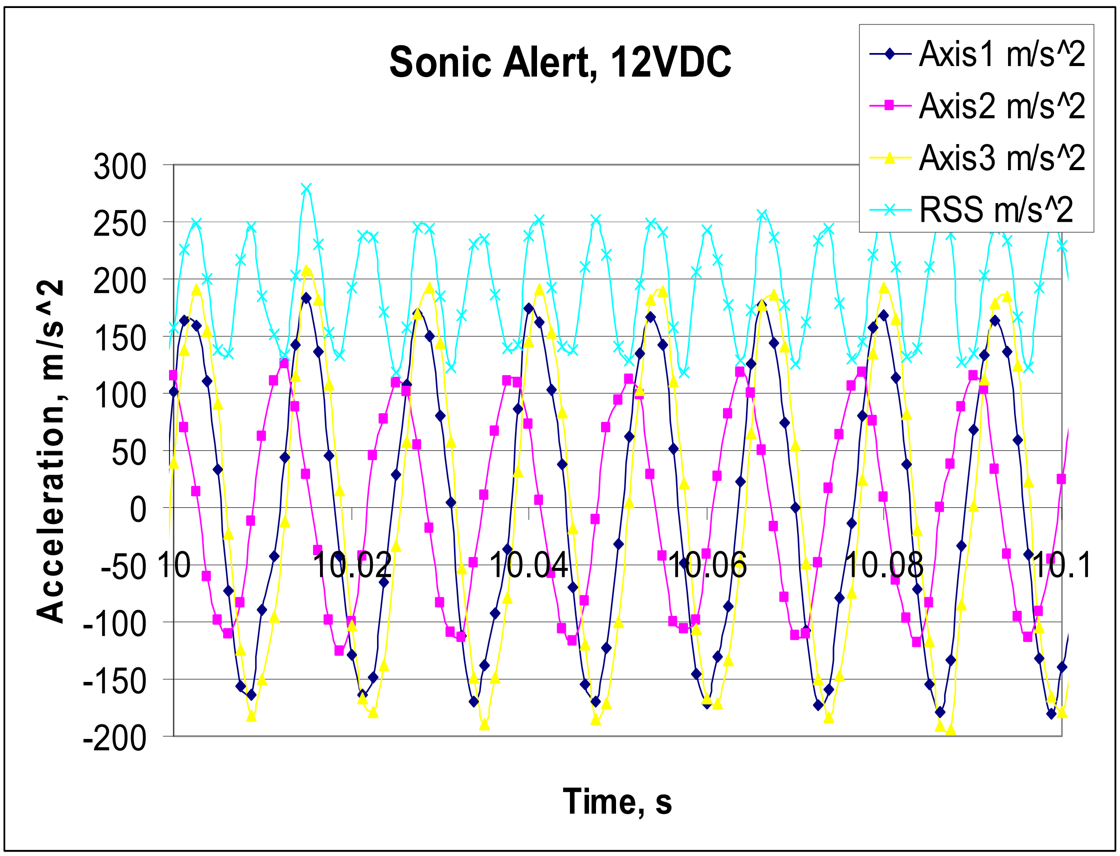

Figure 12. Sonic Alert "Super Shaker Bed Vibrator" (continuous bed shaker) output [Roby, 2005]

Several subjects, especially those with profound deafness, indicated that the continuous bed shaker was used as a non-emergency awakening device. These bed shakers are typically attached to an alarm clock and vibrate when the alarm activates. Early results showed that the deaf subjects awoke to the standard bed shaker less frequently than the hard of hearing and hearing able subjects. During post test interviews, many of the test subjects indicated that they slept through the bed shaker due to what is believed to be conditioning and the "snooze button" effect. Since the deaf subjects were conditioned to the continuous bed shaker as a frequent, daily, awakening method, it is hypothesized that the deaf had been desensitized to this tactile method. Therefore, an intermittent three-pulse bed shaker was introduced into the test series. The intermittent bed shaker vibrates in the same manner as the T3 pattern of the audible smoke detector, as shown in Figure 13. The intermittent bed shaker vibrated for ½ second separated by a ½ second non-vibratory portion, repeated twice, followed by a 1 ½ second pause after the third vibration. The result was a secondary form of the bed shaker providing a tactile stimulus very different from the continuous pulse used by many as a non-emergency signal.

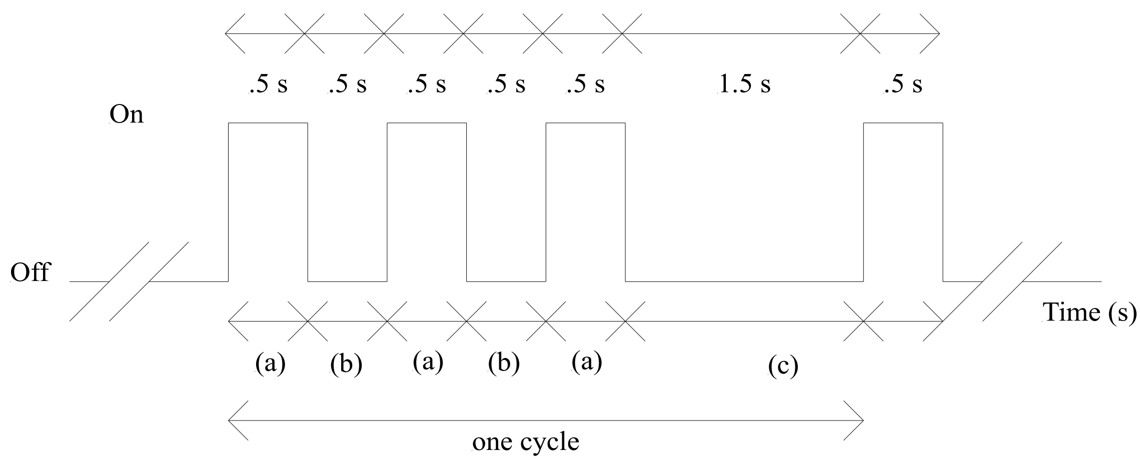

Figure 13. Intermittent bed shaker vibratory pattern

Test Procedure

The decision to test the five devices across three distinct sleep phases for three subpopulations defined by hearing ability yielded a test matrix of eighteen device-sleep stage combinations for each hearing level. The following protocol was established to determine the waking effectiveness of each device in each sleep stage for each hearing subpopulation:

1. The devices were placed and tested within the test room prior to the arrival of the subject. Each volunteer was introduced to the sleep technicians and the engineers

performing the test. The subject was allowed to view the test room and shown each awakening device. Consent forms were collected, and the individual was prepared for the test.

2. Preparation of the subjects was performed by a certified sleep technician. Electrodes were affixed to the subject's scalp to monitor brain activity (sleep stage), and a heart monitor was placed on the person's back to record heart activity. The test started when the patient maintained stage 2 sleep for at least two minutes without change in sleep stage.

3. The number of awakenings per patient was limited to three times per night. A period of 4 hours of undisturbed sleep was required at the end of the testing. Thus, once the subject was asleep and in the desired sleep stage for at least two minutes, different awakening devices were activated for two minutes at a time until the person either awakened or transitioned into a different stage of sleep. The subject was deemed awake when the sleep technician noted the transition from stage one sleep to awake and when the test subject raised their hand.

4. The time to awaken and the device used were recorded on data sheets by hand, and on the computer recordings of each person's brain waves. Times for awakening were compared and confirmed after testing was completed.

5. Once the subject was awakened, they were asked a series of basic questions to help determine his or her level of coherence. The answer to such questions was recorded. The questions asked of the subjects included the following[2]:

    - What awoke you?
    - Who is the president of the United States?
    - What year is it?
    - What city are you currently in?
    - Was the device incorporated into your dreams?

6. The sleep stage of the subject was monitored throughout the single night tests. The alarms were activated and the subjects' responses recorded.

Statistical Models

Several statistical models were used in the analysis of the results. These models include, but are not limited to, a lognormal distribution for time to awaken, a weighted average effectiveness, and a general error assessment.

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[2] It was assumed that the subject would be capable of answering the simple questions when fully coherent. However, since unconfirmed, it cannot be verified that the decrease in coherence led to some of the questions being answered incorrectly. Therefore, the results of this portion of the study have not been included in the final analysis.

To analyze the waking probability of the subject based on the device tested, two values are presented, awakened and not awakened. The two values are coded as 0 for not awakening to the device tested and 1 for waking to the device tested. A generalized probability model was developed to analyze the data.

The response time to awaken was taken into account. A lognormal probability distribution was used to analyze the probability to awaken within a specified time frame.

A weighted average of the data will be presented later to address the results based on the demographics of the United States. Assuming a total American population of 204 million adults, the National Health and Vital Statistics census data suggests 3% of the population is profoundly deaf and 14% is hard of hearing. The effective awakening for each of the hearing sub-populations was multiplied by the percentage of the population that they represented in the United States [CDC, 2004]. Equation 1 was utilized for this study:

$$\text{Weighted Average Awakening Effectiveness} = (A \times 0.83 + B \times 0.14 + C \times 0.03) / 100 \quad (1)$$

A – Number of hearing able subjects awakening per device

B – Number of hard of hearing subjects awakening per device

C – Number of deaf subjects awakening per device

3% - Percentage of US population who are profoundly deaf

14% - Percentage of US population who are partially hearing

83% - Percentage of US population who are hearing able

The effect of various demographics will be analyzed based on the cue, or device tested. These demographics include race, age, sex, and hearing level of the participant. The effect of multiple cues and various cue intensities were not included in this study. The following variables have been analyzed and will be presented:

1. The effect of sleep stage on waking effectiveness
2. The effect of age of participant of waking effectiveness
3. The effect of gender of participant on waking effectiveness
4. The effect of hearing level on waking effectiveness
5. The effect of race on waking effectiveness

Each variable has been analyzed independently and in conjunction with others, for example, the waking effectiveness for a particular device, of a participant of age XX regardless of hearing ability will be defined, as well as the waking effectiveness of a participant of age YY with a specific hearing level.

As mentioned earlier, the population of the sample was divided into three distinct strata: hearing able, hard of hearing and deaf. Based on a total population of 204 million persons, the associated sample error for the study was determined. With a 95%

confidence interval, the variance and the standard deviation was computed for the devices of particular interest. The associated sample errors are provided in the results section. The error assessment provides the associated upper and lower bounds for the waking effectiveness of the various emergency alerting devices.

Summary

Five devices of interest were chosen to be included in this study: the typical audible detector, the strobe, the continuous bed shaker, the intermittent bed shaker and the low frequency audible alarm. The subjects were chosen based on the hearing level and individual demographics. The testing was performed at a certified sleep laboratory in one of three locations: Baltimore, New Jersey or Dallas. The subjects were awakened a maximum of three times during a single night and their response was recorded. Statistical analysis of the data will be included in the results and discussion sections.

RESULTS

Introduction

Data collected from testing was used to assess which device is most reliable in awakening the subject groups to a fire event. The following section outlines the data received from the testing protocol, the specific impact on subject demographics, and the associated error due to sample size limitations. The data is analyzed, providing results which can be categorized by the demographic response to the alarms, the effect of sleep stage on the alarm waking effectiveness and the weighted average effectiveness of the alarms based on the population of the United States.

Limitations

There are several limitations of this dissertation in addition to those provided in the introduction section. These additional limitations relate to the data collection methodology and analysis of this research. These limitations include those on the quantification of the audibility of the typical audible smoke detector and the low frequency audible detector. The measurement of the audibility of these devices is limited to the sensitivity of the measurement devices. Ambient noise, although recorded prior to every sleep test, affects the audibility of the initiation devices. The ambient noise could change up to 20 dBA depending on the location of the test room. Processing of the data is sensitive to the accuracy of the calibration of the sound meter. This calibration device uses an algorithm to convert millivolt readings for peak sound to decibels. The associated error rate with the measurement device is unknown. Ambient noise is incorporated into the sound level readings of the alerting device. The sound levels were taken prior to alarm initiation, ambient sound levels, and recorded.

Sound attenuation is defined as the reduction of intensity of a sound signal due to obstructions or barriers [Camets, 2006]. This reduction is often accomplished through the presence of walls, doors and interior finish of the room; therefore, having doors open or closed or the thickness of walls can influence the sound level of the alarm perceived at a particular location. The attenuation of the alarm sound is not a limitation of this study due to the placement of the alarm within the test room. The alarm was placed in the same room as the subject approximately 10 feet from the bed. In the residential setting, the alarm may or may not be placed within the room that the person resides. Therefore, the reduction in quality or quantity of the sound due to attenuation in the residential setting and its impact on waking effectiveness has not been taken into account.

As with many mechanical devices, the tactile devices tested produced an audible sound when activated. The continuous bed shaker produced a sound measured at 10 - 15 dB where the intermittent bed shaker produced the same sound intensity but in the intermittent pattern. It is unknown how the sound generated by such devices impacted the awakening of the hearing and hard of hearing test subjects.

The effect of a motivated response by the participant on the study results has not been quantified. Motivated response is defined as premature priming to a device. Due to the protocol of this research, the volunteers were allowed to view and activate the test devices. All volunteers were given this option; however, no volunteers requested a demonstration of the devices. It is unclear whether the familiarity of the device prior to sleep affected the motivated response of the subjects.

Overall, the limitations of the results of this study are within the realm of normal for a large research endeavor. Although several quantifiable limitations have been noted, it is not believed that such limitations affected the general conclusions of this project.

Ethnicity Gender and Age

The population sample was chosen based on the demographics of the United States. Ethnicity, gender and age were analyzed to account for any impact such demographics would have on the results of the study. Figure 14 compares the demographics of the United States population with the demographics of the test subjects [U.S. Department of Commerce, 2000]. Table 4 details both the planned enrollment numbers and the number of human subjects that were ultimately included in the study. Hispanic and American Indian males were not successfully recruited to participate in the study.

Two hundred forty two tests were performed on female subjects compared with one hundred and eighty-seven tests performed on male subjects. Women awoke to 68% of the alarm presentations while men awoke to 67%.

Sleep test subject data was also broken down according to the age of the participants. The study participants were predominantly young people under the age of 30; however, efforts were made to extend recruitment to the middle aged and elderly. Figure 15 shows the age distribution the subjects included in this study.

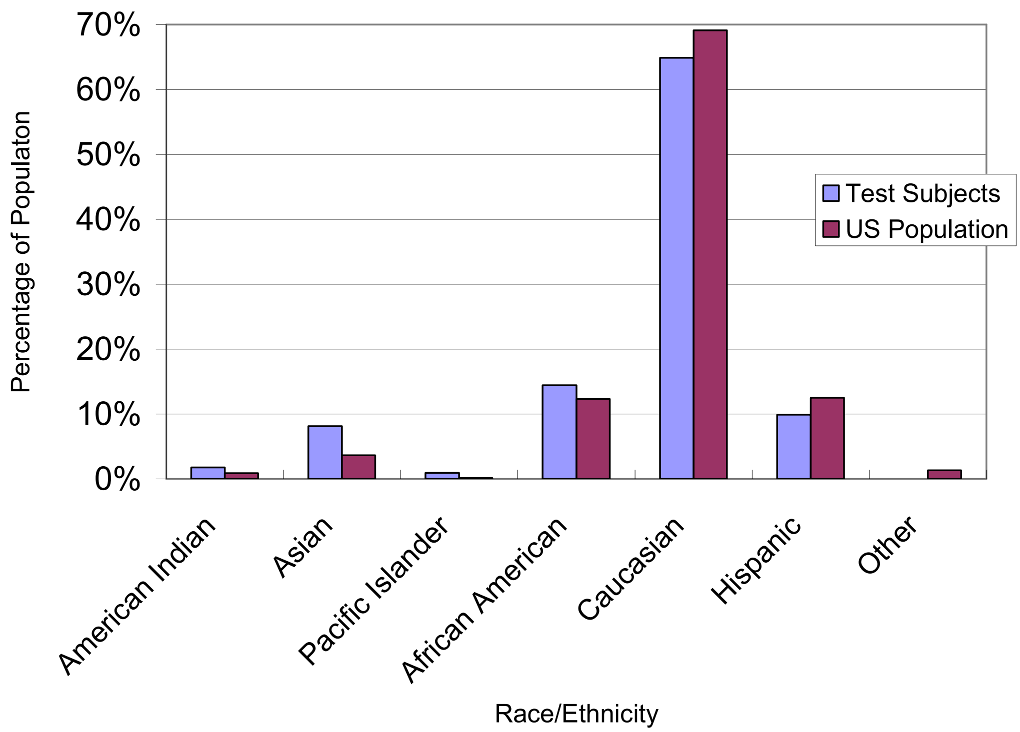

Figure 14. Test sample and United States Population Race demographics

Table 4. Research study enrollment

	Targeted/Planned Enrollment			Inclusion Enrollment		
	Sex/ Gender			Sex/Gender		
Ethnic Category	Female	Male	Total	Female	Male	Total
Hispanic or Latino	9	8	17	8	3	11
Not Hispanic or Latino	52	51	103	53	47	100
Ethnic Category: Total of All Subjects	61	59	120	61	50	111
	Sex/ Gender			Sex/Gender		
Racial Categories	Female	Male	Total	Female	Male	Total
American Indian/ Alaska Native	2	2	4	2	0	2
Asian	4	4	8	5	4	9
Native Hawaiian or Other Pacific Islander	1	1	2	0	1	1
Black or African American	9	7	16	9	7	16
White	36	37	73	37	35	72
Other or Unknown	9	8	17	8	3	11
Racial Categories: Total of All Subjects	61	59	120	61	50	111

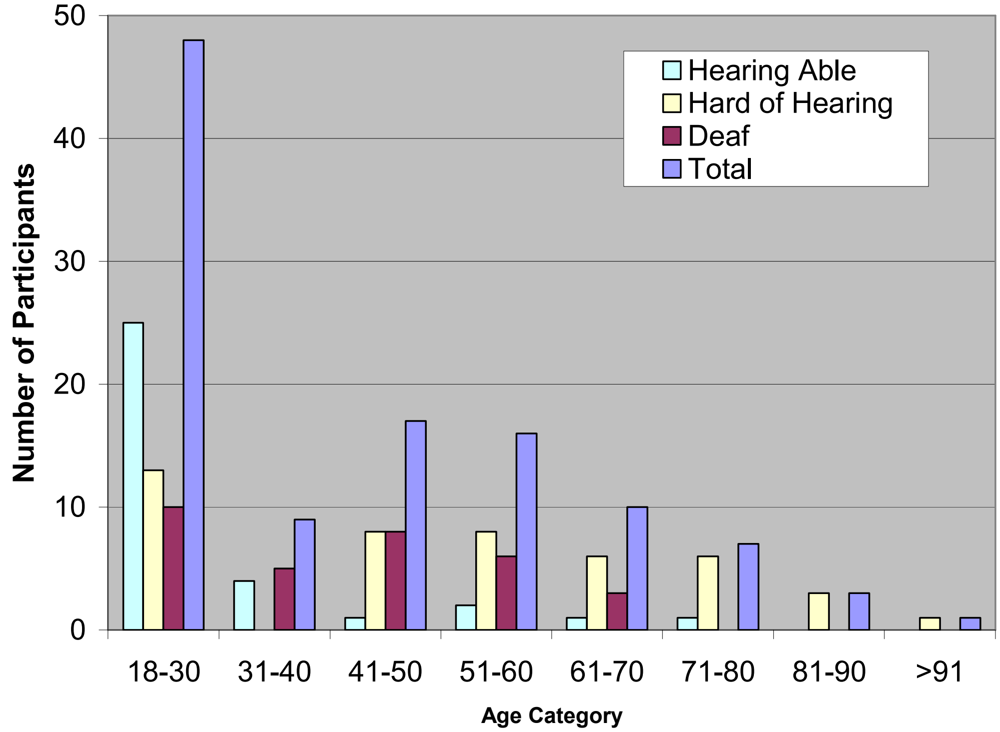

Figure 15. Age demographics of the test sample

<u>Individual Device Results</u>

Four hundred and twenty nine individual tests were performed on subjects classified as deaf, hard of hearing and hearing. One hundred twenty four tests were conducted on subjects with normal hearing, 142 tests were completed for hard of hearing subjects, and 163 tests were completed for deaf subjects. A total of three hundred and eighteen tests will be reported from this point forward due to the deletion of seventy five data points collected for subjects tested with the pillow shaker. The pillow shaker was deemed unsuccessful early in the test procedure and removed from the study. A full explanation on the deletion of the pillow shaker is provided in the next section. With the deletion of the pillow shaker data, a total of 111 subjects were tested, of whom, 32 were deaf, 45 were hard of hearing, and 34 were fully hearing able.

Pillow Shaker

The continuous pillow shaker was introduced into the test series at the commencement of the research, as it is a common awakening device for the deaf community. Seventy five individual tests were performed on the subjects with the continuous pillow shaker. The device was determined to be less than reliable early within the test series. The pillow shaker was placed under a single pillow on the queen size bed in the sleep laboratory. The test bed, as with many residential beds, had two pillows placed on either side of the bed. It was observed early in the research that the test subjects often chose the pillow, or side of bed, without the vibratory device present. After several similar episodes, each subject was questioned prior to the test which side of the bed he or she typically sleeps on. The pillow shaker was then placed on the side of the bed under the pillow that the subject indicated he or she typically slept on. Although this method for pillow shaker placement was deemed more successful, several issues with this device remained.

The pillow shaker, due to the light weight of the pillow, would often vibrate off of the bed. Upon activation, the vibration would often move the shaker from under the pillow to other portions of the bed or to the floor. In addition, the pillow shaker was placed in the immediate vicinity of the subject's head. The hearing and hard of hearing subjects complained about the level of noise that the device made upon activation, introducing questions about the main method of awakening. It could not be determined from the test results whether the awakening effectiveness of the pillow shaker was due to the increased sound in the test laboratory due to the pillow shaker or the vibratory portion of the device. The pillow shaker provides an increase in the ambient noise of the sleeping area, up to five dB, therefore, increasing the required decibel rating of the smoke detector. NFPA 72 mandates that the smoke detector put forth a sound equal to or greater than 15 dB above the ambient sound conditions in the sleeping room [NFPA, 2002].

Due to these issues with the pillow shaker, the device was removed from the experimental program. The device is not included in any of the analysis.

Typical audible smoke detector

The audible smoke detector was tested in 85 separate presentations as shown in Table 5. Twenty-four of the presentations with the audible smoke detector were performed on the hearing able population. The results show that 92%, or 22 of the 24, presentations elicited an awakening response for the hearing able. Twenty-eight individual tests were performed on the hard of hearing subjects with the audible smoke detector. Thirty-three deaf subjects were tested with the audible smoke detector with zero of the deaf subjects responding to this device. Fifty-seven percent, or 16 of the 28 presentations, showed the subjects awakening from sleep.

Table 5. Awakening Effectiveness of the typical audible smoke detector

Hearing		**Hard of Hearing**		**Deaf**	
Total	**24**	**Total**	**28**	**Total**	**33**
Awakened	**22**	**Awakened**	**16**	**Awakened**	**0**
Not Awakened	**2**	**Not Awakened**	**12**	**Not Awakened**	**33**
% Awakened	**92%**	**% Awakened**	**57%**	**% Awakened**	**0%**

Strobe

Ninety-five individual strobe presentations were recorded as shown in Table 6. Thirty-one strobe tests were performed on hearing able subjects. Ten of the 31 presentations for the hearing subjects resulted in an awakening. Twenty-nine strobe presentations were performed on hard of hearing subjects with 34% of the presentations resulting in an awakening. Of the deaf subjects, 20 of the 35 strobe tests resulted in the subject being aroused from sleep.

Table 6. Awakening Effectiveness of the Strobe

Hearing		**Hard of Hearing**		**Deaf**	
Total Tests	**31**	**Total Tests**	**29**	**Total Tests**	**35**
Awakened	**10**	**Awakened**	**10**	**Awakened**	**20**
Not Awakened	**21**	**Not Awakened**	**19**	**Not Awakened**	**15**
% Awakened	**32%**	**% Awakened**	**34%**	**% Awakened**	**57%**

Continuous Bed Shaker

Seventy-eight individual presentations of the continuous bed shaker were performed on test subjects as shown in Table 7. Twenty-six of the presentations were performed on hearing able subjects, 22 on hard of hearing subjects and 30 on deaf subjects. Ninety-two percent of the hearing subjects awoke to the bed shaker. Eighty-two percent of the hard of hearing subjects were aroused by the bed shaker. As with the hearing able subjects 93% of the deaf subjects awoke to the bed shaker presentations.

Table 7. Awakening Effectiveness of the continuous bed shaker

Hearing		**Hard of Hearing**		**Deaf**	
Total Tests	**26**	**Total Tests**	**22**	**Total Tests**	**30**
Awakened	**24**	**Awakened**	**18**	**Awakened**	**28**
Not Awakened	**2**	**Not Awakened**	**4**	**Not Awakened**	**2**
% Awakened	**92%**	**% Awakened**	**82%**	**% Awakened**	**93%**

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Intermittent Bed Shaker

The intermittent bed shaker is the standard bed shaker but with a pattern replicating the three pulse pattern of the typical audible smoke detector. The three pulse bed shaker was introduced after test inception; therefore, only 60 individual presentations of this device were able to be performed. Fourteen tests were performed on the hearing able subjects, 27 tests were presented to the hard of hearing and 19 tests were performed on the deaf subjects. The results are presented in Table 8. Every subject tested awoke to the intermittent bed shaker.

Table 8. Awakening Effectiveness of the intermittent bed shaker

Hearing		Hard of Hearing		Deaf	
Total Tests	**14**	**Total Tests**	**27**	**Total Tests**	**19**
Awakened	**14**	**Awakened**	**27**	**Awakened**	**19**
Not Awakened	**0**	**Not Awakened**	**0**	**Not Awakened**	**0**
% Awakened	**100%**	**% Awakened**	**100%**	**% Awakened**	**100%**

Low Frequency Audible Detector

Thirty-six individual presentations with the low frequency detector were performed as shown in Table 9. The low frequency audible detector was introduced after test inception to assess the ability of the lower frequency device to awaken those with high frequency hearing loss. Five persons with normal hearing were tested with the low frequency audible detector. All hearing able subjects awoke to the low frequency detector. Thirteen individuals classified as hard of hearing were tested with the low frequency detector. Ninety-two percent of the hard of hearing subjects were awakened by the low frequency audible detector compared to only 45% with the typical high frequency smoke detector. Eighteen individual presentations of the low frequency detector were performed on deaf subjects. Two, or 11%, of the deaf subjects were awakened by this detector. It was unclear whether the deaf subjects who awoke to the low frequency did so because of the stimulus, a limitation to the study

Table 9. Awakening Effectiveness of the low frequency audible detector

Hearing		Hard of Hearing		Deaf	
Total Tests	5	Total Tests	13	Total Tests	18
Awakened	5	Awakened	12	Awakened	2
Not Awakened	0	Not Awakened	1	Not Awakened	16
% Awakened	100%	% Awakened	92%	% Awakened	11%

Time to Awaken

The time to awaken for the subjects tested was grouped in increments of 5 seconds. Five seconds was chosen because this was approximately the time period needed to communicate with the sleep technician to confirm awakening and record such event. The devices were activated for a maximum of two minutes; therefore, the waking effectiveness data fits into one of twenty-four time increments. However, for this analysis, a time increment of thirty seconds was chosen to be analyzed. It was found that in the vast majority of cases, regardless of device or hearing level, if the subject did not awaken in the first 30 seconds after device activation, the subject's chance to awaken was drastically diminished.

Audible Smoke Detector

For the subjects tested with the audible smoke detector, as shown in Table 10, the majority of the subjects were awakened in the first 30 seconds after activation. For the hearing able population, 21 of the 22 persons awakened by the audible detector did so within the first thirty seconds. The remaining subject awoke between 31 and 60 seconds. If the subjects were not awakened in the first 30 seconds, their chance to awaken was only 5%.

For the hard of hearing subjects, 88% of the subjects that awoke to the standard audible detector were awakened within the first 30 seconds. One subject was awakened between 31 and 60 seconds and a second subject was awakened in the final time increment. For the hard of hearing subjects, if they did not awaken in the first thirty seconds, the chance to awaken dropped to approximately 10%.

For the deaf subjects, no subject was awakened by the audible detector; therefore, the chance to awaken remained at zero regardless of the time frame.

Table 10. Time to Awaken for Audible Smoke Detector

Time Increment	Number of Subjects (n)	% of Subjects Awakened
Hearing Able		
< 30 seconds	21	95%
31 – 60 seconds	1	5%
61 – 90 seconds	0	0
> 90 seconds	0	0
Total Number Subjects	24	
Total Awakened	22	92%
Hard of Hearing		
< 30 seconds	14	88%
31 – 60 seconds	1	6%
61 – 90 seconds	0	0
> 90 seconds	1	6%
Total Number Subjects	28	
Total Awakened	16	57%
Deaf		
< 30 seconds	0	0
31 – 60 seconds	0	0
61 – 90 seconds	0	0
> 90 seconds	0	0
Total Number Subjects	33	
Total Awakened	0	0

Strobe

For the subjects tested with the strobe, as shown in Table 11, the subjects were awakened most frequently in the time period of initiation to 30 seconds. However, unlike the audible alarm, many subjects awoke after the first 30 seconds. For the hearing able population, 6 of the 10 persons awakened by the audible detector did so within the first thirty seconds. Two subjects awoke in the 31 to 60 second time period and the remaining two subjects awoke between 61 and 90 seconds. If the subjects were not awakened in the first 30 seconds, their chance to awaken dropped to 40%.

For the hard of hearing subjects, 60% of the subjects that awoke to the strobe were awakened within the first 30 seconds. The remaining four subjects were awakened in the 31 to 60 second time period. Similar to the audible detector, for the hard of hearing subjects, if one does not awaken in the first thirty seconds, the chance to awaken drops to approximately 40%.

The deaf subjects reacted in a unique manner to the strobe. The majority of subjects awakened by the strobe, 82%, did so in the first thirty seconds after activation. Two subjects were awakened in the 31 to 60 second period and two subjects in the 91 to 120 second period. A single subject was awakened between 61 and 90 seconds. If a deaf subject did not awaken in the first thirty seconds after strobe activation, the chance to awaken dropped to 18%.

Table 11. Time to awaken for Strobe

Time Increment	Number of Subjects (n)	% of Subjects Awakened
Hearing Able		
< 30 seconds	6	60%
31 – 60 seconds	2	20%
61 – 90 seconds	2	20%
> 90 seconds	0	0
Total Number Subjects	31	
Total Awakened	10	32%
Hard of Hearing		
< 30 seconds	14	88%
31 – 60 seconds	1	6%
61 – 90 seconds	0	0
> 90 seconds	1	6%
Total Number Subjects	28	
Total Awakened	16	57%
Deaf		
< 30 seconds	17	85%
31 – 60 seconds	3	15%
61 – 90 seconds	0	0
> 90 seconds	0	0
Total Number Subjects	35	
Total Awakened	20	57%

Continuous Bed Shaker

For the subjects tested with the continuous bed shaker as shown in Table 12, the subjects were awakened most frequently in the time period of one to 30 seconds. For both the hard of hearing and hearing able populations, all but one subject were awakened in the first thirty seconds. The remaining subject in each hearing subgroup was awakened in the second time increment, 31 to 60 seconds. If the hearing able and hard of hearing subjects were not awakened in the first 30 seconds, their chance to awaken dropped to 4% and 6%, respectively.

For the deaf subjects, 82% of the subjects that awoke to the continuous bed shaker were awakened within the first 30 seconds. Two additional subjects were awakened in the time period of 31 to 60 seconds and an additional subject was awakened in the 61 to 90 second period. The final two subjects awoke to the continuous bed shaker after 90 seconds. If one did not awaken in the first 30 seconds with the continuous bed shaker, the chance to awaken dropped to less than 20%.

Table 12. Time to Awaken for Continuous Bed Shaker

Time Increment	Number of Subjects (n)	% of Subjects Awakened
	Hearing Able	
< 30 seconds	23	96%
31 – 60 seconds	1	4%
61 – 90 seconds	0	0
> 90 seconds	0	0
Total Number Subjects	26	
Total Awakened	24	92%
	Hard of Hearing	
< 30 seconds	17	84%
31 – 60 seconds	1	6%
61 – 90 seconds	0	0
> 90 seconds	0	0
Total Number Subjects	22	
Total Awakened	18	82%
	Deaf	
< 30 seconds	23	83%
31 – 60 seconds	2	7%
61 – 90 seconds	1	4%
> 90 seconds	2	7%
Total Number Subjects	30	
Total Awakened	28	93%

Sleep Stage

Sleep stage was measured throughout the night for every subject tested. Figure 16 highlights the general results of all devices tested and the comparison between sleep stage and waking effectiveness. One hundred and forty two presentations were recorded in the delta stage of sleep with 59% of the subjects being awakened. Ninety-eight tests were performed with 65% of the subjects being awakened in the REM stage of sleep. A total of 114 tests were performed during Stage 2 sleep with the highest percentage of subjects being awakened, 69%.

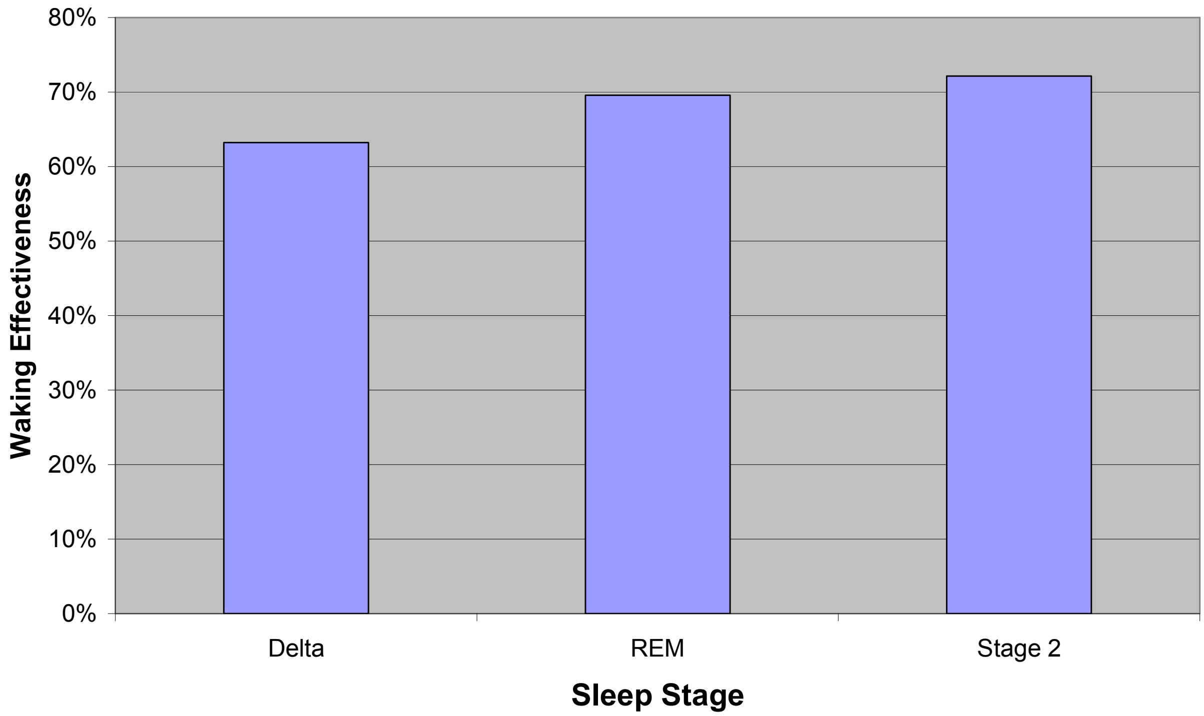

Figure 16. Awakening effectiveness of all devices per sleep stage

For all devices tested, 62% of the subjects awoke in the delta stage of sleep. The results were similar for the REM stage of sleep with 70% of the subjects awakening to all devices. Stage two sleep resulted in the greatest number of awakenings with 72% of the subjects awakening to the devices tested. The results of the sleep stage portion of the study were somewhat surprising; it was assumed that the majority of subjects would awaken during the lightest stage of sleep, REM. However, the majority of subjects awoke to Stage 2 sleep.

Sleep stage and device

Figure 17 details the waking effectiveness of each device tested for the Delta, REM and Stage 2 levels of sleep. The typical audible smoke detector was between 40% and 50% effective in awakening the population regardless of sleep stage. For the delta stage of sleep, the typical audible smoke detector was found to be approximately 45% effective in awakening the subjects tested. For the REM stage of sleep, the subjects awoke in 40% of the alarm initiations compared to 50% for the Stage 2 sleep.

The strobe awoke approximately 30% of the subjects tested in delta sleep compared to greater than 50% of the subjects in REM sleep. Approximately 45% of the subjects awoke the strobe during Stage 2 sleep. The continuous bed shaker awoke the greatest proportion of subjects in Stage 2 sleep with the least proportion of subjects being awakened in the delta stage of sleep. Greater than 80% of the subjects awoke in the delta stage of sleep for the continuous bed shaker. Approximately 90% of the subjects awoke to the continuous bed shaker during the REM stage of sleep and 95% of the subjects during the Stage 2 level of sleep.

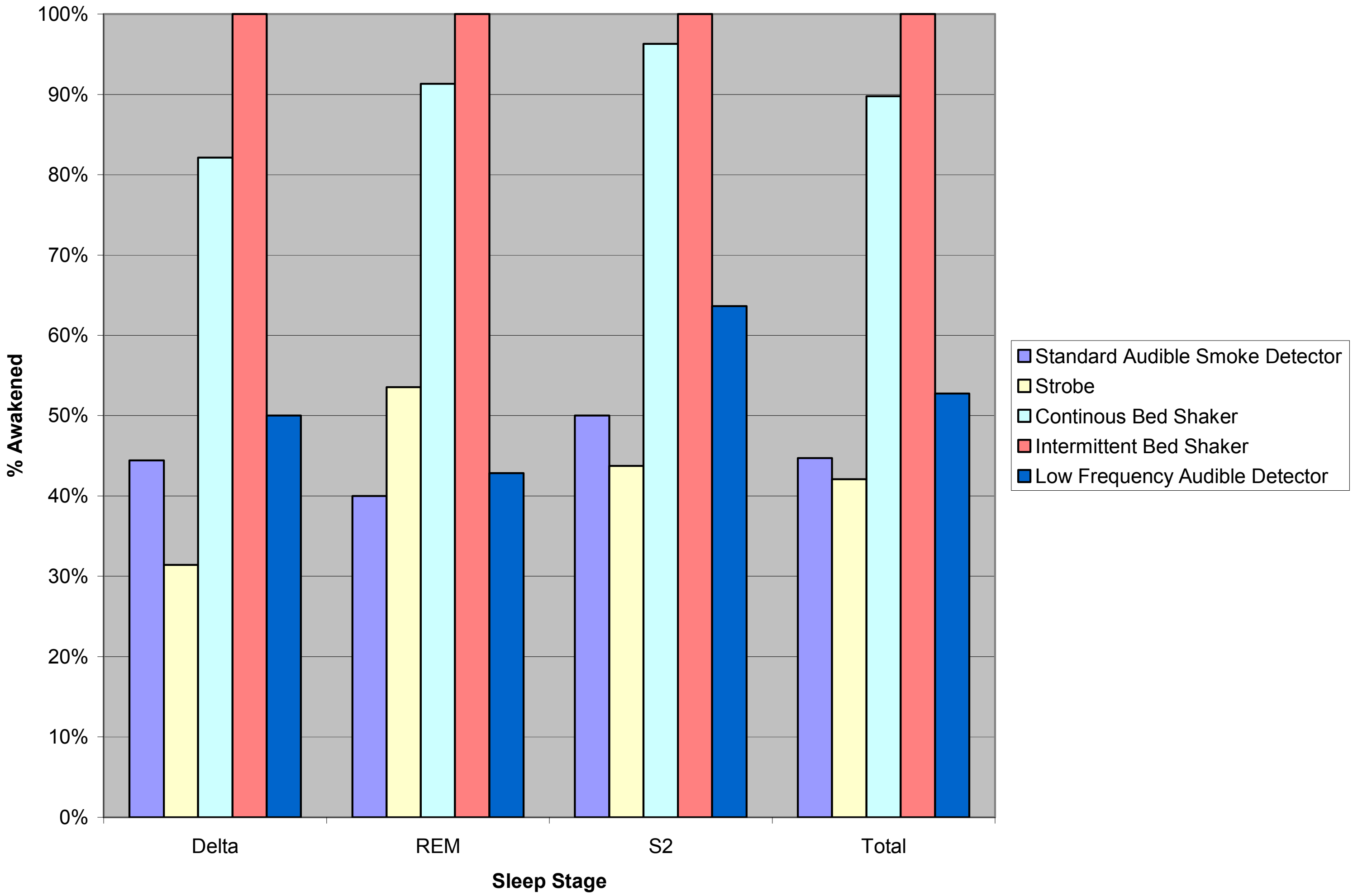

Figure 17. Percentage subjects awakened per device and sleep stage

The intermittent bed shaker showed no deviance in awakening effectiveness during the various sleep stages, awakening all subjects tested regardless of sleep stage.

The low frequency audible alarm showed a similar trend in awakening as the typical audible alarm with the REM stage of sleep being most difficult to awaken from and the

Stage 2 sleep being the most likely stage to awaken from. Fifty percent of the subjects tested in the delta stage of sleep awoke to the low frequency audible alarm. Approximately 43% of the subjects tested with the low frequency audible alarm awoke during the REM stage of sleep and greater than 60% of the subjects awoke during the Stage 2 level of sleep.

Sleep stage and hearing level

Figure 18 highlights the waking effectiveness of the various emergency alerting devices for each sleep stage for the hearing able sub-population only. For the typical audible smoke detector, 100% of the hearing subjects tested in the delta stage of sleep awoke to this device. Seventy-two percent of the subjects in the REM stage of sleep awoke compared to 100% of the hearing subjects being awakened by the typical audible smoke detector in the Stage 2 level of sleep. The strobe was effective in awakening approximately 25% of the subjects during the delta stage of sleep, 40% during the REM stage of sleep and approximately 35% during the Stage 2 level of sleep.

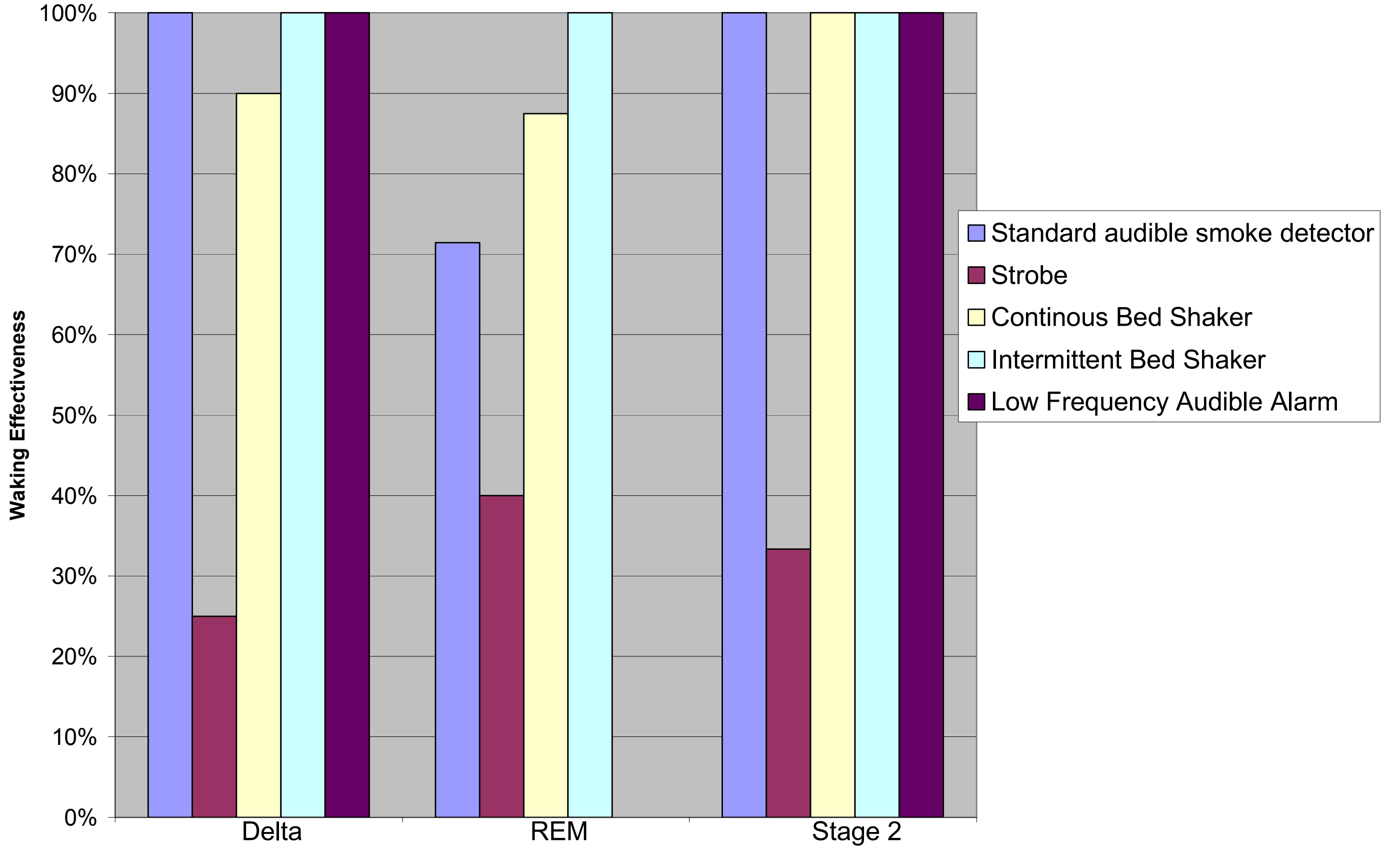

Figure 18. Waking effectiveness per device for each stage of sleep for the hearing sub-population

The continuous bed shaker awakened 90% of the hearing subject during the delta stage of sleep. Slightly less subjects, 88%, of the subjects were awakened during the REM stage of sleep whereas 100% of the subject awoke to the continuous bed shaker during the Stage 2 level of sleep. The intermittent bed shaker was effective in awakening all hearing subjects during ever stage of sleep.

The low frequency alarm was tested on hearing subjects during delta and Stage 2 sleep only. No subjects were introduced to the alarm during the REM level of sleep due to the limited sample size. Of the hearing subjects tested, all awakened to the low frequency alarm during delta and Stage 2 sleep.

Figure 19 outlines the waking effectiveness of each notification device for the hard of hearing subjects tested in delta, REM and Stage 2 sleep. The typical audible smoke detector awakened approximately 55% of the hard of hearing subjects in delta sleep. The awakening effectiveness of the typical audible detector increased to greater than 60% when tested in the REM stage of sleep. This same device was determined to be 55% effective in awakening the hard of hearing subjects in the Stage 2 level of sleep.

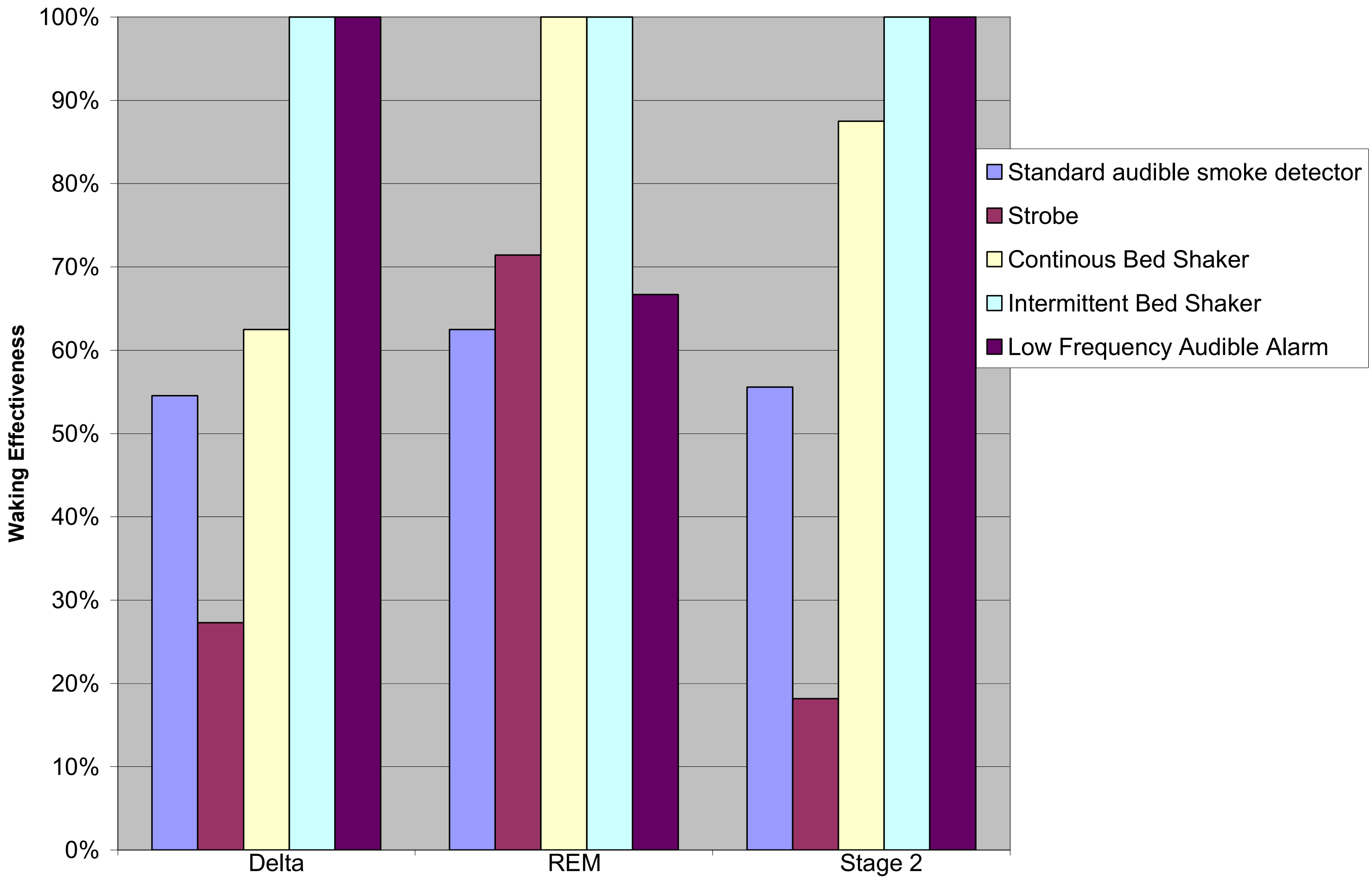

Figure 19. Waking effectiveness per device for each stage of sleep for the hard of hearing sub-population

The strobe was most effective in awakening the hard of hearing in the REM stage of sleep with approximately 70% of the subjects responding to this notification device. The strobe was 27% effective in awakening the hard of hearing in the delta stage of sleep and less than 20% effective in awakening this group during Stage 2 sleep.

As with the strobe, the continuous bed shaker was most effective in awakening the hard of hearing during REM sleep with 100% of the subjects being awakened during this sleep stage. During delta sleep, 62% of the hard of hearing subjects were awakened to the continuous bed shaker and 100% of the hard of hearing subjects were awakened during the Stage 2 level of sleep. The intermittent bed shaker showed no deviation in effectiveness across each sleep stage with 100% of the subjects being awakened in delta sleep, REM sleep and Stage 2 sleep.

The low frequency audible alarm was most effective in awakening the hard of hearing during delta sleep and Stage 2 sleep with all subjects, 100%, being awakened by this device. The low frequency audible alarm was approximately 67% effective in awakening the hard of hearing during REM sleep.

Figure 20 shows the waking effectiveness of each device tested on the deaf sub-population during each sleep stage. The typical audible smoke detector did not awaken any of the deaf subjects, and is therefore, not shown in the figure. The strobe was successful in eliciting an awakening response from 41% of the deaf subjects in delta sleep. Approximately 52% of the deaf subjects were awakened during REM sleep and 75% were awakened during Stage 2 sleep.

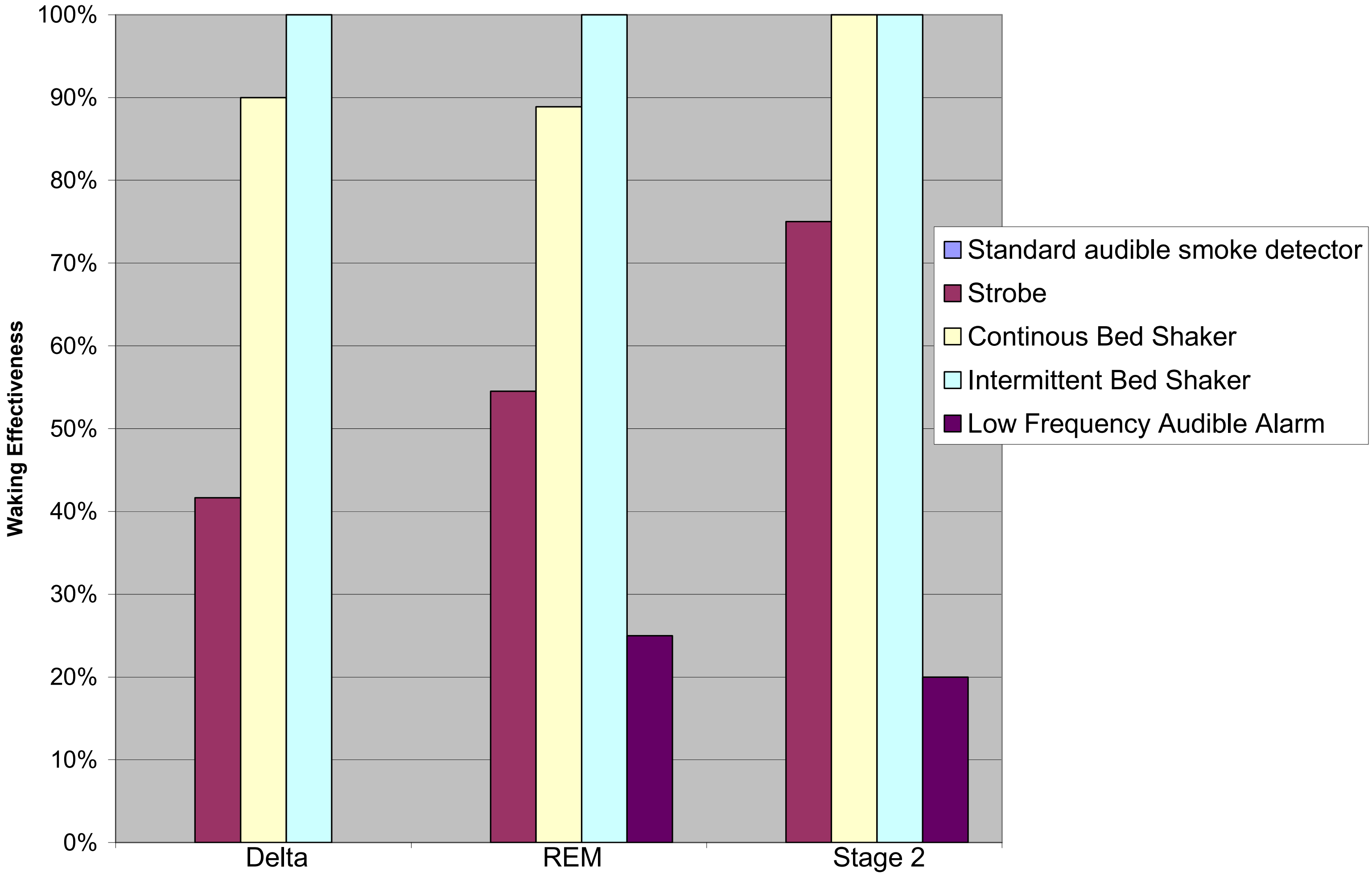

Figure 20. Waking effectiveness per device for each stage of sleep for the deaf sub-population

The continuous bed shaker was effective in awakening 90% of the deaf subjects during delta sleep and 89% of the subjects during REM sleep. All of the deaf subjects tested with the continuous bed shaker, 100%, were awakened with the continuous bed shaker.

The intermittent bed shaker was successful in awakening all the deaf subjects tested regardless of sleep stage; therefore, no difference can be noted in the effectiveness of the intermittent bed shaker when tested in differing sleep stages.

The low frequency audible alarm was unsuccessful in awakening any of the deaf subjects during the delta stage of sleep. Twenty-five percent of the deaf subjects showed a response to the low frequency audible alarm during REM sleep and 20% were awakened during Stage 2 sleep.

Error Assessment

A sample error assessment was performed to assess the significance of the results. The variance and standard deviation of the sample based on a binomial distribution were calculated for each of the devices tested. The test sample sizes for each device tested are presented in Table 13. Eighty-five individual audible smoke detector presentations were included in the study. Twenty-four of the audible smoke detector presentations were performed on the hearing able subjects, 28 on the hard of hearing subjects, and 33 on the deaf subjects. The strobe was tested in 95 individual presentations with 31 strobe tests performed on the hearing able subjects, 29 on the hard of hearing and 35 on the deaf. The continuous bed shaker was tested 78 times with 26 presentations on the hearing able subjects, 22 presentations were performed on the hard of hearing, and the remaining 30 presentations on the deaf subjects. The low frequency audible detector was added later in the test protocol; therefore, only 36 individual presentations were recorded. Five persons who were classified as hearing able were tested with the low frequency audible detector, 13 hard of hearing and 18 deaf subjects. The intermittent bed shaker was tested on 50 individual subjects with 14 presentations recorded for the hearing able, 27 for the hard of hearing and 19 for the deaf subjects.

Table 13. Sample size of each device tested for each hearing subgroup

Sample Size	Typical audible smoke detector	Intermittent Bed Shaker	Strobe	Continuous Bed Shaker	Low Frequency Audible Detector
Total sample size	85	50	95	78	36
Hearing Able	24	14	31	26	5
Hard of Hearing	28	27	29	22	13
Deaf	33	19	35	30	18

The correlation population for this calculation was based on that of the United States: 204 million adults. Eighty-three percent of the population is considered hearing able, or 169 million, 14% of the population is hard of hearing, or 28 million, and 3% of the population is deaf, or six million Americans [CDC, 2004]. Based on a 95% confidence interval, the variance, or measure of spread from the mean, was calculated and shown in Table 14. The standard deviation based on the associated variance was calculated and presented in Table 15. The calculated sample size error for each device tested is presented in Table 16.

Table 14. Variance for each device sample

Variance	Typical audible smoke detector	Intermittent Bed Shaker	Strobe	Continuous Bed Shaker	Low Frequency Audible Detector
Total Sample	21.2	4.7	23.7	19.5	9.0
Hearing Able	6.0	3.5	7.7	6.5	1.2
Hard of Hearing	7.0	6.7	7.2	5.5	3.2
Deaf	8.2	4.7	8.7	7.5	4.5

Table 15. Standard deviation for each device sample

Standard Deviation	Typical audible smoke detector	Intermittent Bed Shaker	Strobe	Continuous Bed Shaker	Low Frequency Audible Detector
Total Sample	4.6	2.2	4.9	4.4	3.0
Hearing Able	2.4	1.9	2.8	2.5	1.1
Hard of Hearing	2.6	2.6	2.7	2.3	1.8
Deaf	2.9	2.2	3.0	2.7	2.1

Table 16. Calculated sample error for each device sample

Sample Error	Typical audible smoke detector	Intermittent Bed Shaker	Strobe	Continuous Bed Shaker	Low Frequency Audible Detector
Total Sample	11%	22%	10%	11%	16%
Hearing Able	20%	26%	18%	19%	44%
Hard of Hearing	19%	19%	18%	21%	27%
Deaf	17%	22%	17%	18%	23%

The associated device awakening effectiveness for each hearing sub-group with the calculated error rates, as shown by the error bars, based on test sample size is presented in Figure 21. For the hearing subgroup: the typical audible smoke detector, the continuous bed shaker, the intermittent bed shaker, and the low frequency audible alarm all showed an upper bound waking effectiveness of 100%. The lower bound waking effectiveness for the hearing subjects for the typical audible smoke detector, the strobe, and the intermittent bed shaker was between 72% and 74%. The lower bound waking effectiveness for low frequency audible alarm tested on the hearing subjects tested is approximately 55%. The strobe had a mean waking effectiveness of 32% for the hearing subjects and an upper bound waking effectiveness of 50% and a lower bound waking effectiveness of approximately 15%.

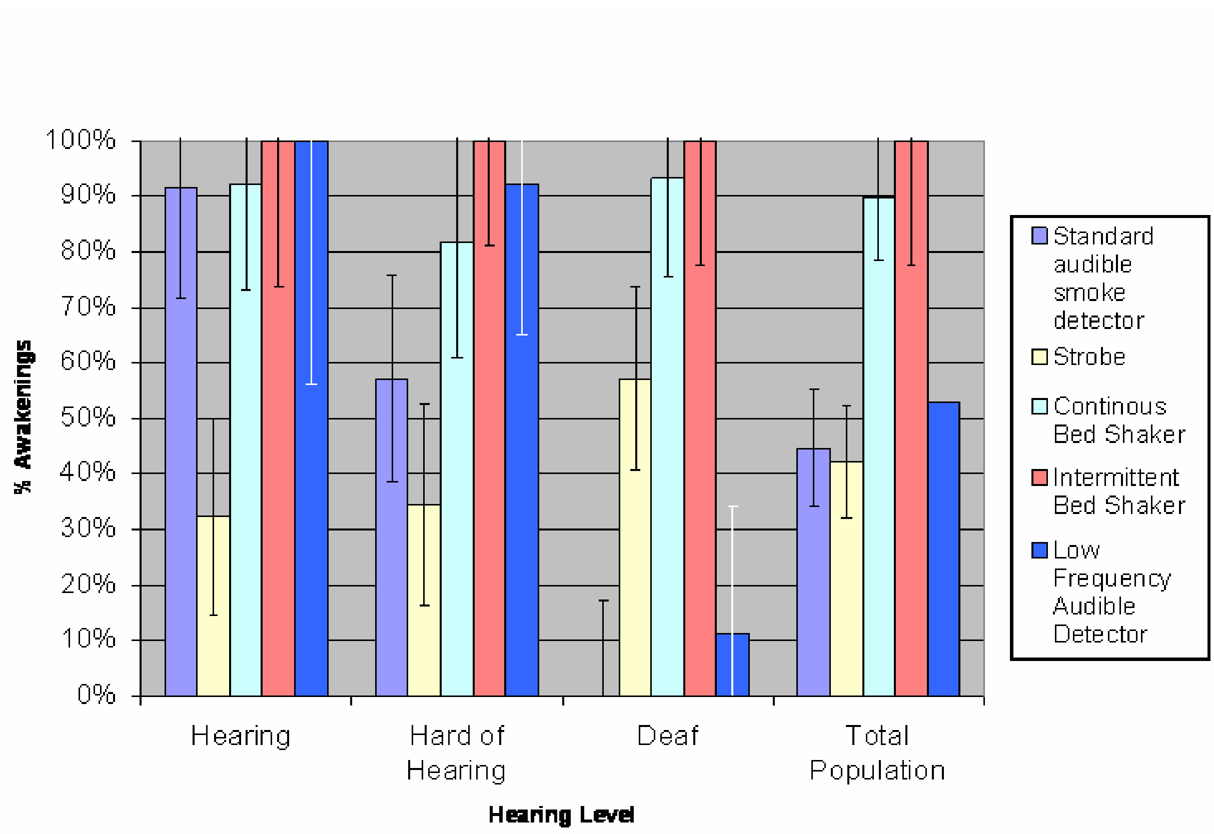

Figure 21. Waking effectiveness of the emergency notification devices with error incorporated

The continuous bed shaker, the intermittent bed shaker and the low frequency alarm when tested on the hard of hearing subjects had an upper bound waking effectiveness of 100%. The continuous bed shaker has a lower bound waking effectiveness for the hard of hearing subjects of 60% where the intermittent bed shaker has a lower bound waking effectiveness of 80%. The low frequency audible alarm has been shown to have a lower bound waking effectiveness of 65% when tested on the hard of hearing subjects. The typical audible detector has a mean waking effectiveness for the hard of hearing of 58%. The lower bound waking effectiveness for the typical audible smoke detector for the hard of hearing is 38% and the upper bound waking effectiveness was calculated at 75%. The strobe was the least effective device for the hard of hearing with a mean waking effectiveness of 35%, an upper bound waking effectiveness of 53% and a lower bound waking effectiveness of 18%.

Weighted Average

The results of this study were weighted against the population of the United States to account for the differences in demographics between the subpopulations of hearing able, hard of hearing, and deaf. Assuming a total American population of 204 million adults, the National Health and Vital Statistics census data suggests 3% of the population is profoundly deaf and 14% is hard of hearing [CDC, 2004]. Equation 1 was utilized for this analysis.

The weighted average as compared to the raw data presented earlier is significant in that it specifically relates the waking effectiveness of each device for each hearing subgroup to the United States population as a whole instead of generalizing for all hearing levels. Again, it can be seen that the intermittent bed shaker is the most effective across all hearing abilities at 100% effectiveness followed by the continuous bed shaker and low frequency audible detectors with 91% and 90% respectively. The typical audible smoke detector is only 83% effective when taking into account the true demographics of the American population. The least effective of all of the devices was the strobe which yielded only 33% waking effectiveness for the general population. The results of the weighted average effectiveness calculation are shown in Figure 22.

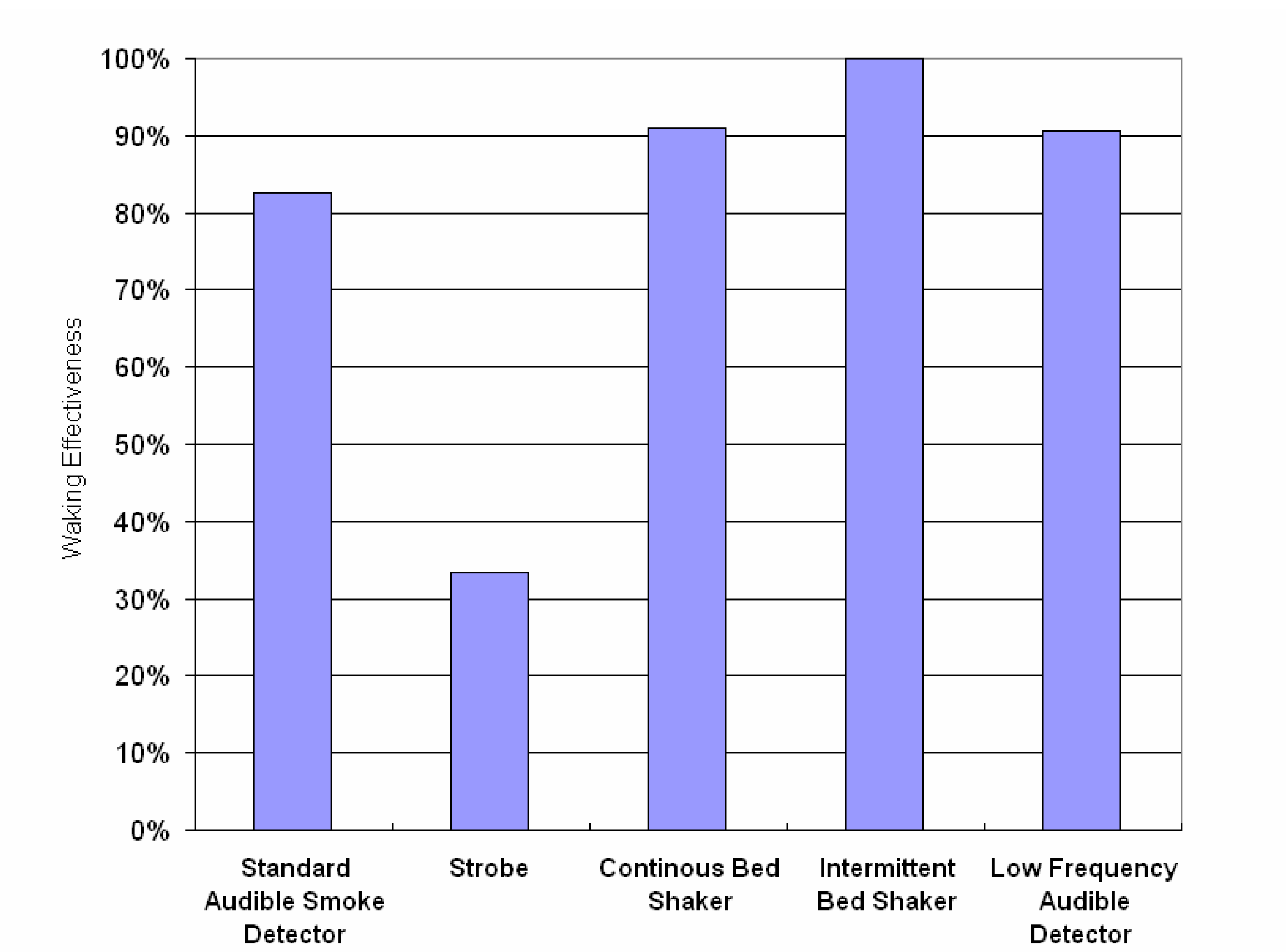

Figure 22. Weighted average effectiveness of the devices based on the United States Population

DISCUSSION

Introduction

Significant points have been brought forth in this study. First, the typical audible smoke detector, which is installed in many homes throughout the United States, was found to be only 83% effective when weighted across the US population on the basis of hearing ability. This means that of the 204 million Americans over 18, thirty-five million might not awaken to the typical smoke detector sold in the United States. The strobe is the recognized alternative to the smoke detector, however, the results of this study have shown that the strobe is an ineffective device for awakening persons to an emergency. Overall, the vibratory devices provide an adequate mechanism to awake those to an emergency event.

Statistical Significance

Based on the data presented in the results section of this thesis, the statistical significance of the work has been computed. The effectiveness of each device, or point estimate, was ordered from least effective to most effective for each hearing subgroup. The difference between two point estimates was determined by subtracting the lesser effectiveness of the device first in order from the second device in order. For example, from the hearing able subgroup, the strobe was determined to be the least effective device and had a point source, or effectiveness, of 32%. The continuous bed shaker was the second ordered device with the next highest effectiveness of 92%. The difference between point source for the continuous bed shaker, 92%, and the point source for the strobe, 32%, was calculated at 60%. The margin of error, E, between the two data sets was calculated based on a 95% confidence interval with equation 2 [Chow, 2003].

$$E = z_c\,[(p_1\,(1 - p_1) / n_1) + (p_2\,(1 - p_2) / n_2)] \qquad (2)$$

Where

z_c is the z-score for the 95% confidence interval (1.96)

p_1 is the point source, or effectiveness, of the lesser effective emergency alerting device

n_1 is the sample size of the lesser effective emergency alerting device

p_2 is the point source, or effectiveness, of the more effective emergency alerting device

n_2 is the sample size of the more effective emergency alerting device

The confidence interval is determined through equation 3.

$$(p_1 - p_2) - E < \text{“}(p_1 - p_2)\text{”} < (p_1 - p_2) + E \qquad (3)$$

If $[(p_1 - p_2) - E]$ or $[(p_1 - p_2) + E]$ is less than zero, the two effectiveness values are determined to be in a statistical dead heat and therefore, statistically insignificant. [Chow, 2003]

For the hearing able subgroup, the difference between the results for the strobe device and the continuous bed shaker were determined to be statistically significant. However, the results of the continuous bed shaker, typical audible smoke detector, low frequency audible detector and the intermittent bed shaker were determined to be statistically insignificant.

The results of the study indicate that for the hearing able subgroup, the difference between the effectiveness of the tactile devices, typical audible smoke detector and the low frequency device is negligible. The hearing able person would be provided with equivalent notification from any of these devices. However, the comparison between the effectiveness of the strobe and the other tested devices is not negligible. The hearing able person would be at a significant disadvantage to be notified to an emergency event if the strobe was used alone.

The confidence interval was calculated for the hard of hearing subgroup results. The effectiveness of devices tested was ordered from least effective, the strobe, to the most effective device, the intermittent bed shaker. The strobe point source effectiveness was determined to be 34% for the hard of hearing subgroup where the point source effectiveness of the typical audible smoke detector was 57%. The results for the strobe and typical audible smoke detector, calculated to the 95% confidence interval, were determined to be statistically insignificant. The difference between the strobe when compared to all other devices tested, except for the typical audible smoke detector, on the hard of hearing subjects yielded results that were considered statistically significant. The results of the typical audible smoke detector were compared to the continuous bed shaker. The difference between the effectiveness of the typical audible smoke detector and the continuous bed shaker were determined to be statistically significant to the 95%

confidence level. The test results of the continuous bed shaker, low frequency audible smoke detector and the intermittent bed shaker were compared. It was determined that the difference between the effectiveness of the continuous bed shaker, the low frequency audible detector and the intermittent bed shaker were not statistically significant.

Based on the statistical analysis of the results for the hard of hearing population, it can be determined that the typical audible smoke detector and the strobe provide similar waking effectiveness. However, when these two devices are compared to the continuous bed shaker, the low frequency audible detector and the intermittent bed shaker, the results indicate that the strobe and typical audible smoke detector provide significantly less protection. The continuous bed shaker, low frequency audible detector, and the intermittent bed shaker were determined statistically to be in a dead heat. Therefore, based on the results of this study, the hard of hearing can be provided with a series of devices that are significantly better in alerting than the typical audible smoke detector and the strobe. These devices are the continuous bed shaker, the low frequency audible alarm and the intermittent bed shaker.

The results for the devices tested on the deaf subgroup were much different than the results for the hard of hearing and hearing groups, The point source effectiveness of the typical audible smoke detector was zero where the point source effectiveness of the low frequency audible smoke detector was 11%. At a 95% confidence interval, the difference between the effectiveness of the audible smoke detector and the low frequency detector for the deaf is not significant. However, when these two devices are compared to the strobe, the continuous bed shaker and the intermittent bed shaker, the audible detectors are less effective. The strobe, with a point source effectiveness of 57%, and the continuous bed shaker with a point source effectiveness of 93% was compared and it was found that the results of the two devices were statistically significant. When the continuous bed shaker was compared with the intermittent bed shaker, the results were not statistically significant.

Overall, for the deaf subgroup, the audible smoke detector and the low frequency audible detector were found to have statistically insignificant results, therefore, both devices performed at the same level. The audible detectors, the strobe and the tactile devices provide statistically different levels of protection with the tactile devices being most effective. When comparing the two tactile devices, the continuous bed shaker and the intermittent bed shaker, the results indicated that they performed at the same level for the deaf subgroup.

When comparing each hearing sub group, several conclusions can be made. First, the vibratory devices were found to be significantly more effective than the visual device. Only in the hearing and hard of hearing subgroups did a type of device, the audible detectors, perform at the same statistically significant level. This analysis shows that when the population is expanded infinitely, the difference between the results of individual device types (i.e., bed shaker vs. intermittent bed shaker) is diminished. However, the difference between the device activation methods (i.e., visual vs. tactile) proves more significant.

Demographics

Gender

Two hundred forty two tests were performed on female subjects compared with one hundred and eighty seven tests performed on male subjects. Women awoke to 68% of the alarm presentations while men awoke to 67%. No significant difference was found regarding awakening effectiveness per device or sleep stage when based on gender. Table 17 shows the difference in awakening effectiveness for males and females for each of the sleep stages.

Table 17. Comparison of awakenings for males and females during each sleep stage

Females			
	DELTA	**REM**	**Stage 2**
Total Female Subjects Tested	111	59	79
Awakened	74	39	52
Not Awakened	37	20	20
% Awakened	67%	66%	72%
Males			
Total Male Subjects Tested	63	56	68
Awakened	36	42	49
Not Awakened	27	15	19
% Awakened	57%	73%	72%
Difference between Sexes			
% Awakened	10%	7%	0

Kimura [Kimura, 1998] noted differences in cyclic nature of sleep when comparing men and women. Women are more heavily influenced by cyclic sex hormones during sleep. These hormones affect the sleep wake structures of the female. During the female menstrual cycle, women often feel sleepier during the luteal phase and are most active during ovulation. The role of female hormones in regards to quality and quantity of sleep in the woman is not fully understood; the female hormones provide a drive to sleep more and submit to deeper stages of sleep during times of breeding and conception.

Although not fully verified in this study, women of child bearing age have a propensity to maintain a deeper level of sleep and duration of sleep during the night [NHLBI, 2003]. Intuitively, the effectiveness of emergency alerting devices would be expected to decrease for the deeper stages of sleep. From the study, and as written in the previous section, sleep stage does not appear to dramatically impact the effectiveness of emergency alerting devices in regards to awakening the test subject. Also, based on the results of the study, women awoke to the devices tested in the same propensity as the male subjects of this study.

Several factors may explain the propensity of the male and female subjects to awaken to the devices tested in the same frequency. Every subject was asked to fill out a pre-study questionnaire and it was confirmed that none had any known sleep disturbance. The sleep stage data was forwarded to medical professionals from Sleep Services of America and analyzed for any sleep disturbances. Of the 111 subjects tested, none were found to have a sleep disturbance that would have impacted the test results. Therefore, any propensity for the male or female to exhibit a sleep disturbance was equated by ensuring no sleep disturbances were present. Second, prior to activation of any alarm, the sleep stage was determined to be consistent for at least thirty seconds. At the time of activation, the specified sleep stage was known for each subject. Therefore, the propensity for one sex to fall or stay in a deeper stage of sleep and the impact on the results could not be determined. It can be assumed that based on the analysis of sleep stage, the effectiveness of the emergency alerting devices are not decreased in the Delta stage of sleep. Therefore, one would not expect the sex of the subject to impact the test results.

Race

The subjects were classified as one of seven races: American Indian, Asian, Pacific Islander, African American, Caucasian, Hispanic, and non-Caucasian. Table 18 highlights the results for all devices based on race for the hearing population.

Table 18. Hearing able subject results based on race

Race	Number of Subjects	% of Subjects Awakened
American Indian	4	75%
Asian	12	100%
Pacific Islander	0	N/A
African American	25	84%
Caucasian	117	82%
Hispanic	16	88%
Non-Caucasian	57	88%

From the table, one can see that the Asian subjects were awakened 100% of the time to the emergency alerting devices where the American Indian subjects were awakened only 75% of the time. In order to adequately analyze such results, the confidence interval and the significance of the results must be obtained. Based on a similar analysis performed for the Statistical Significance section of this chapter, the results can be observed at the 95% confidence interval. At the 95% confidence interval the difference between the results for the American Indian subjects, the lowest performing group, and the average across all races, 83%, is not statistically significant. Therefore, it has been determined that the impact of race on waking effectiveness is not significant for the hearing able subgroup.

The results for the hard of hearing subgroup in relation to race varied greatly from one ethnicity to another as shown in Table 19. Eleven Hispanic persons with hearing loss were tested with less than half awakening to the devices tested. Two American Indian subjects were tested with each of them responding to the devices. The average effectiveness for the hard of hearing for all the devices was determined to be 72%. With a confidence level of 95%, it was determined that the difference between the lowest performing group, the Hispanic, and the highest performing group, the American Indians, compared to the average across all races was deemed statistically insignificant. This statistical anomaly is due to the low sample sizes of the races besides Caucasian.

Table 19. Hard of Hearing subject results based on race

Race	Number of Subjects	% of Subjects Awakened
American Indian	2	100%
Asian	4	75%
Pacific Islander	0	N/A
African American	10	80%
Caucasian	133	74%
Hispanic	11	45%
Non-Caucasian	27	67%

The deaf subject results in regards to race are presented in Table 20. The average effectiveness of all devices for the deaf subjects was 65%. The lowest performing deaf race subgroup was the Pacific Islander with only 50% of the subjects responding the alarm. Close to seventy percent of the Caucasian subjects responded to the devices. With a 95% confidence interval, the results for the deaf in regards to race are in a statistical dead heat. It can be deduced that the difference between the races for the deaf subgroup is insignificant.

Table 20. Deaf subject results based on race

Race	Number of Subjects	% of Subjects Awakened
American Indian	0	N/A
Asian	18	61%
Pacific Islander	4	50%
African American	23	65%
Caucasian	141	69%
Hispanic	16	63%
Non-Caucasian	61	62%

There has been little research on the impact of race on quality of sleep and waking effectiveness from emergency alerting devices. African Americans tend to have a higher rate of sleep disordered breathing, while twice as many African Americans as Caucasians have this disorder [NHLBI, 2003]. Hispanic children have been found to have less Stage 3 and 4 sleep than there Caucasian counterparts suggesting that racial differences may impact sleep stage. The cause for such discrepancies between the races is unknown and unproven. The results of the current study indicate that race does not play a factor in the waking effectiveness of emergency alerting devices.

The assumption was made that the emergency alerting devices chosen for each race subgroup were distributed evenly across each race. For the race subgroups with the larger sample sizes, greater than 20 persons, this assumption is verified. However, for the race subgroup with minimal sample sizes, the chosen devices could not be distributed evenly and the impact of this on the results is unknown.

Age

Children and the elderly are disproportionately likely to perish in a residential fire [Bruck, 2001]. It is estimated that approximately 20% of all residential fire deaths are those over the age of 70 years [Barillo, 1993]. Figure 23 highlights the distribution of deaths in residential fires for various aged victims. In a two year study by NFPA, an estimated 72 victims over 70 years of age died in residential fires where the smoke detector was reportedly operational [Fahy, 2004]. It has been believed in the fire protection community and reported in the *Journal of the American Medical Association (JAMA),* that this disproportionate death rate for the elderly in residential fires was due in part to mobility and/or hearing impairments [Marshall, 1998]. The research presented here has shown that the aged population does not awaken to the typical audible detector in the same manner or frequency as the general public. This lack of awakening to the standard alarm for the aged population, even when hearing is defined as "normal", may influence the trend for the elderly to disproportionately die in residential fires.

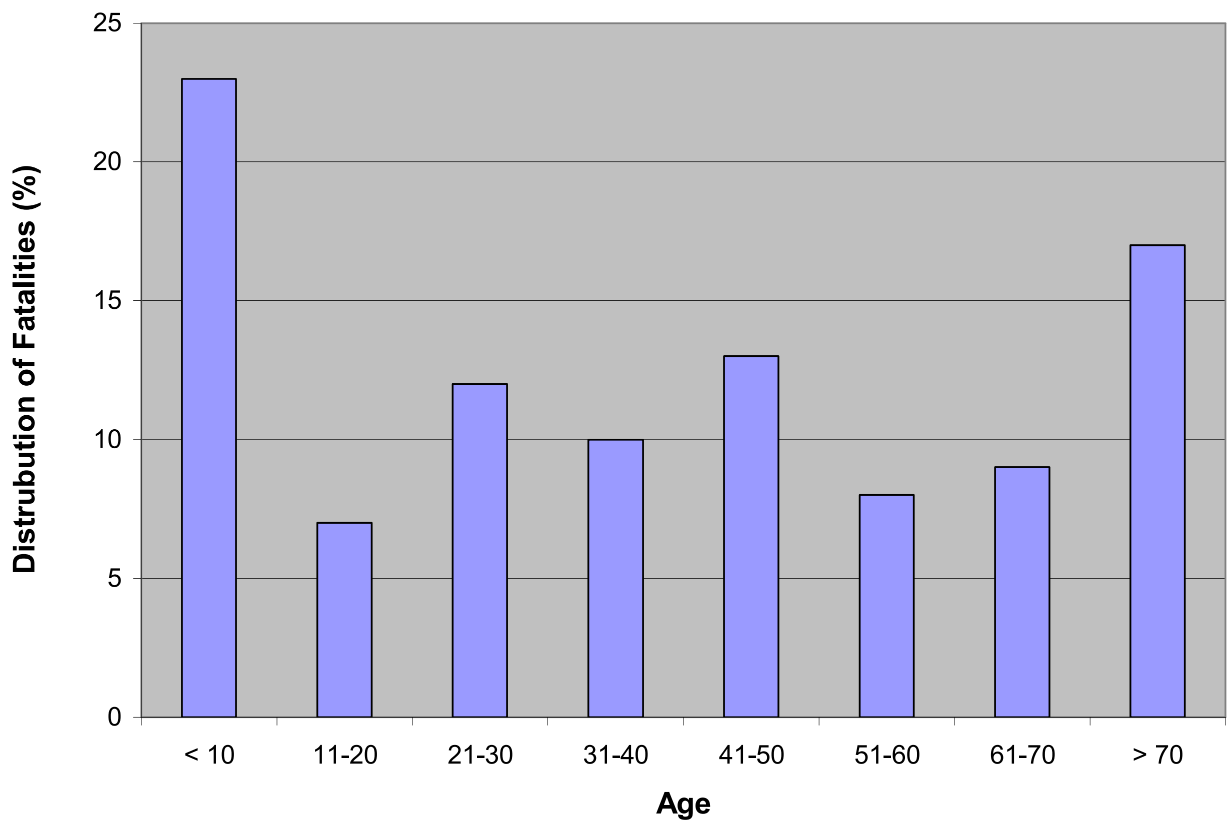

Figure 23. Age distribution of residential fire deaths in New Jersey during the period 1985-1991 [Barillo, 1993]

The results of the study indicate that the aged subjects, those over 60 years of age, with "normal" hearing (20 dB or less across the frequency spectrum of 250-8000 Hz) do not awaken to the typical audible smoke alarm in the same propensity as the subjects less than forty years of age. Figure 24 shows the decreased waking effectiveness of the typical audible alarm as the age of sample population increases.

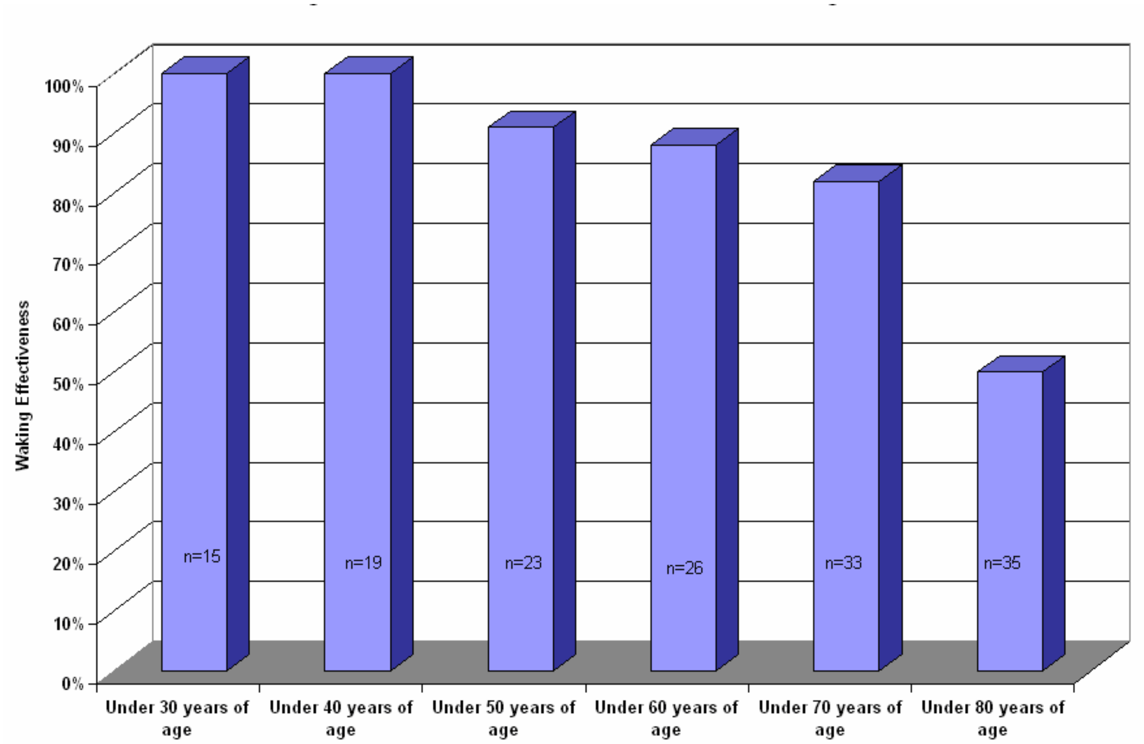

Figure 24. Waking Effectiveness of typical audible Alarm for Specific Age Groups

For the subgroup under 40 years of age, 100% of the subjects tested with "normal" hearing awoke to the audible alarm within two minutes of activation. For those under 50 years of age, 88% responded by awakening to the alarm. The effectiveness of the typical audible smoke detector decreased to 85% for the subjects less than 60 years of age. For those under 70 years of age, the waking effectiveness of the typical audible smoke detector was again reduced to 80%. For the under 80 year old population, the alarm was least effective, with only 47% of the subjects responding.

Table 21 highlights the individual results for each hearing able age subgroup tested with the typical audible smoke detector. For the group less than 40 years of age, all 19 test subjects were awakened to the typical audible smoke detector. The group aged 41 to 50 years awoke only half of the time. For the group aged 51 to 60 years, 67% awoke to the typical audible smoke detector compared to 57% for the group in their sixties. For the oldest subgroup, those 71 to 80 years of age, half awoke to the typical audible smoke detector.

Table 21. Individual performance of each hearing able age group for waking to typical audible smoke detector

	Age Group					
	<30 yrs.	31-40 yrs.	41-50 yrs.	51-60 yrs.	61-70 yrs.	71-80 yrs.
No. of Subjects	15	4	4	3	7	2
% Awakened	100%	100%	50%	67%	57%	50%

It should be noted that the results of this portion of the study are not statistically significant but do show a downward trend in waking effectiveness of the audible alarm as the subject group increases in age.

A recent study by Dr. Bruck of Victoria University in Melbourne, Australia corroborates the findings of the study. Forty-five adults in between the ages of 65 and 85 years were tested with four audible devices. For the high T-3, consistent with the typical audible alarm, subjects between the ages of 75 and 85 years of age, compared with those 65 to 74 years of age, needed a higher decibel sound to elicit awakening. This study also tested lower frequency T-3 alarms, 500 Hz, and an alternating frequency T-3 patterned audible alarm. The results of the study indicate that the older population awaken more frequently to the low frequency alarms, indicating, a propensity for the recognition of lower frequency sounds in the aged [Bruck, 2006].

Based on the data presented in Figure 24, the statistical significance of the data for the elderly has been computed. The effectiveness of the typical audible smoke detector for each age subgroup, or point estimate, was ordered from least effective to most effective for each age group. The difference between two point estimates was determined by subtracting the lesser effectiveness of the group first in order from the second group in order. For example, from the under 80 years of age subgroup, the audible detector was determined to have a point source, or effectiveness, of 50%. The under 70 year old age group was the second ordered group with the next highest effectiveness of 80%. The difference between the two groups was calculated at 30%.

Sleep problems are reported by approximately 40% of the elderly. These sleep disorders include light sleep, frequent awakening and daytime fatigue. The older generation tends to maintain sleep in the lighter stages and often do not reach the deep stages of sleep

[Cruickshanks, 1997]. This fact would make one believe that the elderly would be more likely to awaken to outside stimulus, such as an audible alarm. The body of research presented indicates that the elderly awaken less frequently to the audible alarm, inconsistent with the sleep disorders present in the elderly.

Several reasons exist as to why an aged subject would not awaken to the typical audible alarm in the same frequency as one less than 40 years of age. A literature search of medical, engineering, psychology and sleep literature has been performed to address this issue. The first possible cause to the decreased arousal in the aged is the use of medicinal drugs. A study was performed among adults over the age of 65 years to attempt to account for the amount of prescription and non-prescription drug use. About one quarter of the respondents reported using no prescription or non-prescription medicines in the two days prior to being surveyed; a large majority reported using two or fewer medicines only, and use of non- prescription medicines was reported more often than prescription medicines (56% vs. 48%) [Ballantyne, 2006]. The use of drugs such as alcohol, central nervous system stimulants, beta blockers, corticosteroids, decongestants, antidepressants, nicotine and thyroid hormones in the elderly may have an impact on the ability and ease in waking to outside stimulus [Henkel, 2003]. This cannot be confirmed, however, due to the lack of data on the medicinal use of the subjects during this study. The participants were asked prior to the sleep study not to use medicines that would impact their sleep. Due to privacy issues, the exact medications the subjects were exposed to could not be confirmed prior to the sleep tests. It was left to the untrained judgment of the subjects to determine if they believed their medicinal use impacted their sleep.

It is often difficult to distinguish a single cause of sleep problems in the elderly [Merck, 2006]. Effects of disease are often difficult to distinguish from the effects of age. There are few models of which to judge the “normal” sleep pathology in the elderly, therefore, diagnosing sleep disturbances becomes difficult. The relevant sleep pathology in the elderly may be asymptomatic or display no outward sign of a problem. Several additional options have been hypothesized but an in-depth analysis of the possible neurological issues associated with age and sleep is outside the expertise of this researcher. These issues include, but are not limited to:

- In aged persons, the neurologic N2-P3 (or N200-P300) complex is decreased. This complex is needed to evaluate an outside stimulus and allow the body to transverse from sleep to awake [Bastuji, 2003].

- The neurologic components needed to evaluate and classify stimuli during sleep are delayed and replaced by high amplitude frontal-central negative waveforms. The results of this change in the elderly is unknown in regards to awakening [Kemp, 2006]

- It is estimated that close to 32% of all aged subjects have some form of narcolepsy, cataplexy and/or paradoxical sleep onset. The implications of these disorders to awakening to stimuli have not been researched [Bastuji, 2003].

- Sleep spindle activity increases as the human ages. The role of sleep spindles is hypothesized to preserve sleep. With the increase activity of sleep spindles in the aged, the body attempts to preserve sleep, therefore, the ease in awakening to outside stimuli is decreased [Bowersox, 1985].

Strobe Results

Although not required in residential homes per NFPA 72 [NFPA 72, 2002] the strobe is the recognized alternative to the typical audible smoke detector for the hearing impaired. The ADA mandates that audible-alarm notification be supplemented by visible-alarm notification (such as strobe lights) to alert people with hearing disabilities [ADA, 1994].

From the data presented in the Results section of this dissertation, it is apparent that the strobe is an ineffective mechanism to alert those to a fire emergency. On average, the strobe awoke 42% of the subjects tested. It is unclear why the strobe performed so poorly. One hypothesis which could not be proven is the propensity for vision problems in the test sample. The vision history was not questioned prior to the commencement of the test. It could be inferred that if one had poor vision, it would impact their ability to see the light of the strobe.

Also, unclear from this study is the effect of an increasing light source on the results. Strobes are provided in intensities ranging to 177 cd for residential use. The strobe chosen for this study was 110 cd. The impact on a subject's sleep when tested with a strobe with a higher light intensity is unknown.

Overall, the results of this study in relation to the strobe contradict the results set forth in the UL 1971 document. To reiterate, the UL study utilized 110 cd strobes in homes where subjects were sleep or sleep stage could not be confirmed. The UL reported the 110 cd strobe awoke 100% of the deaf adults not using medication compared to 57% of the current study's deaf subjects. It is unknown why the discrepancy between the UL data and the data procured in this research exists. The measurement of sleep stage throughout this study guaranteed that the subjects were asleep. Since UL did not measure sleep stage or monitor the subjects during sleep, it is unknown from the UL data if all subjects tested were asleep or in the deeper stages of sleep.

Literature by Bowman [Bowman, 1995] indicates a similar waking effectiveness to the strobe as presented in this study. The strobe which has been accepted within industry as an alternative to the standard audible detector has been shown to be less than 55% of the subjects tested and corroborated by the Bowman study.

Overall, the tests by Bowman correspond with the data presented in the current study. The strobe which has been accepted within industry as an alternative to the typical audible detector has been shown to be less than 55% of the subjects tested and corroborated by the Bowman study. Despite the sensitivity of many deaf people to awakening devices that use light, the awakening effectiveness for the strobe was much less than the baseline effectiveness of the hearing able to the audible detector.

Waking Order

The waking effectiveness of each of the emergency alerting devices was tested during one of three sleep stages: Stage 2, delta, and REM sleep. The results of the study were analyzed to test the impact of waking order on subject response. Each subject was awakened a maximum of three times during the single night tests. It was unclear if the effect of awakening order impacted the results. For example, hypothetical hearing able subject number 5 was awakened with the typical audible smoke detector during Delta sleep in the first test of the night. Hypothetical hearing able subject number 72 was not awakened by the typical audible smoke detector during Delta sleep in the third test performed on him/her during the test night. It had to be deduced whether the response of subject number 5 was impacted by the fact that the typical audible smoke detector was activated in the first test of the night compared to the response of subject 72 when the typical audible smoke detector was activated in the third test of the evening following two additional devices and two possible previous awakenings.

Allan of the University of Maryland developed a protocol to test the hypothesis that waking order impacts the results of the study [Allan, 2006]. The data provided was sorted out by test subject ID numbers and each test subject was reviewed at individually to see what devices were introduced in the particular sequence. The response of the individual subject was recorded and whether or not they had multi-introductions during any sequence. Furthermore, within each sequence, the type of sensory notification was determined; either motion, visual, or sound. The typical audible smoke detector and low frequency audible smoke detector were classified as sound sensory notification devices. The intermittent bed shaker and continuous bed shaker were classified as motion sensory notification devices. The strobe was classified as a visual sensory notification device.

Success, or waking effectiveness, was determined if the subject was awakened; if not, a new device was presented until a success was seen. The sequence of device presentation was recorded for each of the three awakenings in addition to each success or failure within sequence 1, 2, or 3.

If the subject failed to awake and sleep stage was maintained during the first introduction of a device, a second device was randomly chosen and activated. It was not evident by observation if the sequencing or multiple introductions, could affect a subject's response. Data analysis is performed to determine if subjects were becoming habituated or sensitized to notifications. Additional analysis was performed to distinguish any pattern in response behavior depending on the introduction order.

Two methodologies were introduced by Allan to provide a means to establish any noticeable patterns in subject wakening behavior. This behavior may be a function of device introduction sequencing. If a success occurred, the data was divided according to the sleep stage for which the device was presented. The perspective only considers if the device was introduced first, second, or third. For instance, if subjects' were becoming primed or habituated during the course of testing, increased or decreased response behavior would be evident. This would suggest that multiple device introductions impacted the test results.

Results

Typical audible smoke detector

During the delta phase of sleep in hearing able subjects, the audible alarm was 100% effective for any sequencing. It was never tested in the second sequence, but fully effective when presented to the subject first or third. For REM sleep, while in the first and second sequences the alarm was 100% effective. The sequence success rate decreases to about 33% when the subject was presented with the audible alarm in the third sequence of REM sleep. For Stage 2 sleep, the audible alarm device was 100% effective for each sequence presented to the subject.

From this data, decrease in effectiveness during REM sequencing is the only notable variance. By the third trial, subjects have apparently gained a bias and ultimately become unresponsive, concluding that perhaps the sound is insignificant and ultimately become unresponsive. Additionally, REM sleep is associated with dreaming.

Strobe

Strobe testing during delta shows a decrease in effectiveness from the first to second introductions. The first introduction is roughly 42% and unsuccessful in the second. The strobe was not tested for a third introduction. Hearing able subjects also showed a decrease in the success rate during REM sleep for the strobe. When it was introduced second, it was about 66% successful; in the third trial it was only 30% successful. The data for stage two sleep shows that the strobe is successful at the same rates; 33% for sequence 1 and 2. It was not tested in S2 for sequence three.

Again, there is a decrease in effectiveness as the introduction sequence number increases. The reasoning for the reduction in effectiveness for the REM stage of sleep is unknown.

Continuous Bed Shaker

The pattern for the delta phase of sleep shows that the success rate of the continuous bed shaker increases with sequencing. It increases by 25% from the first introduction to 100% effective when introduced second and third. The bed shaker was not tested first in sequencing, but trends from second and third testing show an increase in response during REM of about 25%. For the Stage 2 sleep, the bed shaker awoke all hearing able subjects tested. By the third introduction, success rates during all stages of sleep indicated a 100% success rate. The increasing success rate could be due to the priming of the response from the subject to earlier awakenings. When comparing this device to the visual and audible devices, it is possible that subjects may have been primed to the tactile motion of the bed shaker and were not primed to the visual or audible cues.

Time to Response

The estimated probability of a subject to respond to an alarm within the two minute activation period was quantified using a lognormal distribution. The time to response value is critical because if the subject does not awaken prior to the alarm being damaged or destroyed by the fire, the subject will most likely succumb to the fire.

The lognormal distribution is defined with reference to the normal distribution [Evans, 2000]. A random variable is log normally distributed if the logarithm of the random variable is normally distributed. This distribution is often used in generally reliability analysis in estimating cycles to failures, material strengths, and time to a specified event. The lognormal distribution is always positive in value and often heavily weighted towards zero.

Two hundred and ninety one subjects were awakened by an alarm within the two minute activation period. The vast majority of the subjects, 138 persons, were awakened less than one second after activation of the alarm. A histogram portraying the time distribution of awakening of the subjects is shown in Figure 25 with five second increment periods. It is clear from this plot that the frequency of awakening is heavily weighted towards the one second interval and decreases as the interval reaches 120 seconds.

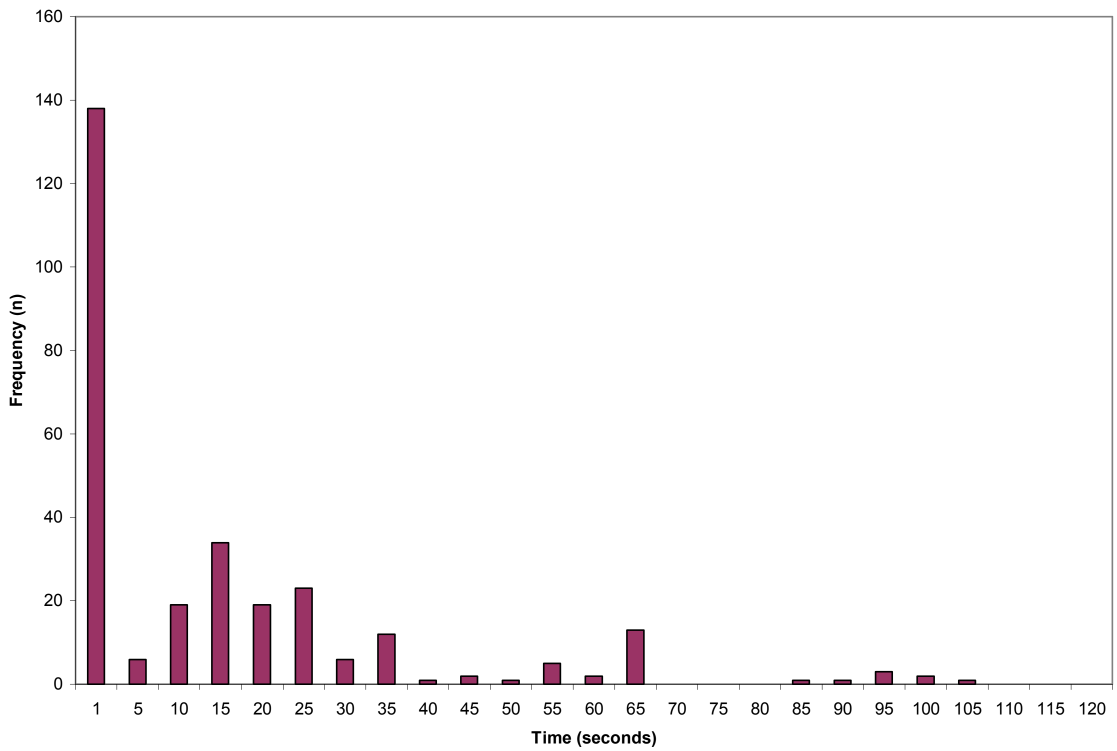

Figure 25. Histogram comparing frequency of awakening with time from alarm activation

The time variable, t, can be modeled as lognormal since it can be thought of as the multiplicative product of many small independent factors [Young, 1962]. The probability distribution function (PDF) of the lognormal distribution is estimated by

$$\exp\left(-\left[\frac{\ln(x)-\mu}{\sigma}\right]^2 \Big/ 2\right) \Big/ \left(x\sigma\sqrt{2\pi}\right) \tag{4}$$

Where x = the time to response (awakening) of the subject

μ = standard deviation or 22.88 seconds

σ = mean or 14.67 seconds

The probability distribution function is plotted and shown in Figure 26.

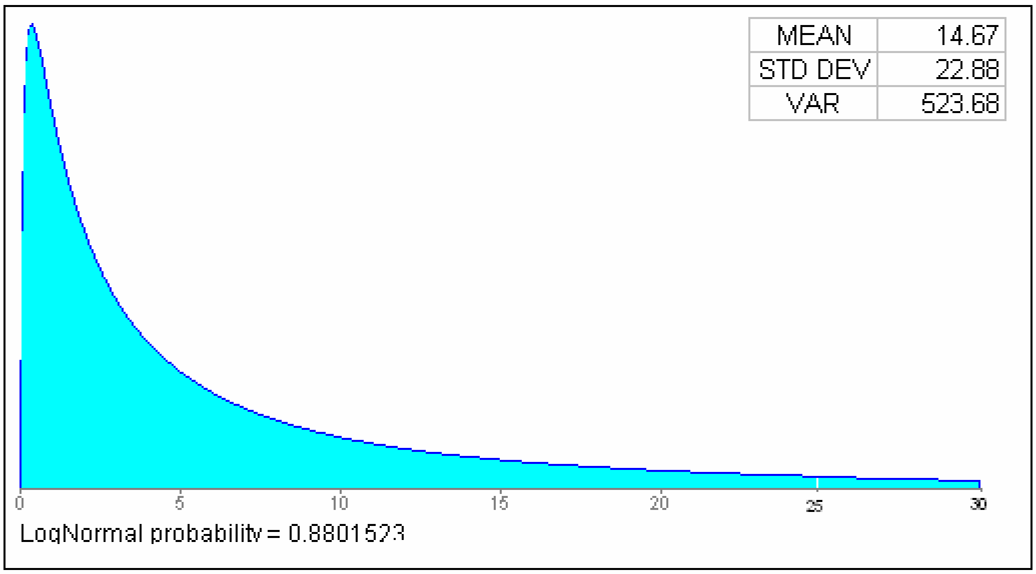

Figure 26. Probability distribution for lognormal time to response data

To analyze the lognormal distribution statistically, one must transform the log normally distributed data into a normal distribution [Evans, 2000]. The time data (x) will be transformed to be used in the normal distribution by taking the natural logarithm of the time to response or LN (x).

Since the sample size (n) is large, the normal distribution can be approximated by two parameters in the normal distribution represented by N (μ, σ) [Young, 1962]. The mean of the time data was determined to be 14.7 seconds. The standard deviation is calculated 22.9 for the sample. Taking the natural logarithm of the mean and standard deviation, the normal distribution can be estimated by the following: N (1.52, 1.59) where, the natural log of the mean is 1.52 seconds and the natural log of the standard deviation is 1.59.

The above mentioned method can be verified by using the inverse transformation from normal to lognormal [Evans, 2000].

$$\mu = E(x) = e^{\mu + \sigma^2 / 2} \qquad (5)$$

$$\sigma^2 = \text{var}(x) = (e^{\sigma^2} - 1)\, e^{2\mu + \sigma^2} \qquad (6)$$

Where x is the time to response of the subject in seconds of the original distribution data

By calculation:

$\mu = 16.18$ and $\sigma = 21.67$

The calculated values are within 10% of the experimental values.

Taking the integral of the pdf at the time of 30 seconds, the probability that a subject will awaken within 30 seconds after alarm activation was determined to be 88%.

$$P(0 \leq t \leq 30) \approx .88$$

Overall, the results of the analysis indicate that the majority of subjects, who would awaken to the emergency notification devices, would do so in the first 30 seconds. The chance to awaken drops to less than 12% if the subject does not awaken within the first 30 seconds.

Bruck reported that a subject's probability of awakening decreased significantly after 60 seconds [Bruck, 1995]. The results of this study and the cure model analysis indicate that the critical time to awaken is within the first 30 seconds after alarm activation. If the subjects do not awaken within the 30-second window, the chance of awakening decreases to less than 14% for all hearing levels across all stages of sleep.

The time to awaken is significant because it is directly related to the amount of time available for a person to complete the egress process and escape a dangerous situation. Also, alarm devices may be thermally degraded in the heat of a fire and fail to remain active throughout the fire event. It is estimated that smoke detectors become thermally degraded when the surrounding air temperature reaches 92 ºC; and they are no longer able to produce sound at 114 ºC [D'Souza, 2001]. In a typical bedroom fire, thermal degradation of a smoke detector can occur in as little as 45 seconds. Thus, awakening to the alarm within the first 30 seconds is crucial, especially if the alarm signal is terminated due to thermal degradation after that time. Therefore, awakening to an alarm within the first 30 seconds is crucial to providing the subject adequate time to escape the fire.

CONCLUSIONS

Introduction

The research attempted to identify the waking effectiveness of several emergency notification devices available to the deaf and hard of hearing communities. The goal of this project was to provide a means for which persons with hearing loss can choose a device that will improve the chances for surviving a fire for a hearing impaired individual. The results indicate that the standard recommended devices were not successful in awakening the deaf, hard of hearing, and aged populations. It has been hypothesized and proven that alternative emergency notification devices can provide these risk groups with waking probabilities equal to the waking probability of the typical audible smoke detector for the average hearing able adult.

General Conclusions

It is readily apparent that the hard-of-hearing and the deaf populations of America are at significant risk for succumbing to fires while sleeping in their homes because of the prohibitive expense or unavailability of a stimulus appropriate smoke detection system. Any device on the market for hard of hearing or deaf people should be able to provide the same degree of waking effectiveness as what is currently offered the hearing able in the form of an audible smoke detector. This study demonstrates that hearing able people awaken to the typical audible smoke detector 96% of the time, independent of sleep phase. For the hearing able population, the tactile devices and typical audible smoke detector were most effective in awakening these subjects. The strobe was found to be the least effective device for awakening the hearing able population.

For the hard of hearing population, the tactile devices and low frequency alarm provided the most effective awakening mechanism. The typical audible smoke detector and the strobe performed poorly with the hard of hearing population.

The deaf population was awakening most frequently with the tactile devices. The strobe was effective in awakening approximately half of this population while the audible detectors did not awaken any deaf subjects.

The results were also assessed for the impact of age on outcome. The data addressed above agree with other data that demonstrate that the elderly are at a significant disadvantage of succumbing in fires given their failure to awaken in a timely manner. For the hearing able subjects tested with the audible smoke detector, the effectiveness of this stimulus dropped significantly for those under eighty years of age compared to those less than seventy years of age. This result supersedes mobility as the main cause of failure of the aged to escape from emergency situations.

The time to awaken was assessed. Using a lognormal probability distribution for the data set, it was determined that the majority of the subjects were awakened within the first thirty seconds after alarm activation. This value is correlated through the work of Bruck

[Bruck, 1995] who found that approximately 90% of her study subjects were awakened within the first thirty seconds after alarm activation.

Further Research

More research is needed on the waking effectiveness of emergency alerting devices for at risk groups, specifically, children and the elderly. This research has shown that age impacts one's ability to awaken to the typical audible alarm; however, a conclusive explanation as to why this occurs is not available.

Additional research should be provided which addresses the limited effectiveness of the strobe as an awakening device. It is unclear whether a higher intensity light would impact the results for the strobe.

A larger sample size for the individual devices would limit the error associated with this study. Additional work with a larger number of subjects may provide results that are statistically significant.

Additional study on the effect of sleep stage on waking effectiveness may provide insight on why conclusive results were not gained on that portion of this study.

Finally, research quantifying various tactile stimuli may provide results that are effective in awakening all subjects' regardless hearing level, age, demographic or sleep stage.

REFERENCES

ADA. "ADA Standards for Accessible Design." United States Department of Justice, 24CFR Part 36, 1994.

Ahrens, M., "The U.S. Fire Problem Overview Report: Leading Causes and Other Patterns and Trends," NFPA Publication, 2003.

ANSI S3.4. "American National Standard Procedure for the Computation of Loudness of Noise." American National Standards Organization, 2005.

Armitage, R. "Sex Difference in Slow Wave Activity in Response to Sleep Deprivation." *Sleep Research Online*, Vol. 4, Issue 1 (2001).

Arnberg, P. "Sleep Disturbances Caused by Vibrations from Heavy Road Traffic." *Journal of Acoust. Soc. Am.*, Vol. 88, Issue 3 (1990).

Akerstedt, T. "Awakening from Sleep." *Sleep Medicine Reviews.* Vol. 6, No. 4 (2002).

Ballantyne, P. "Use of Medicines by Community Dwelling Elderly in Ontario." www.socserv2.socsci.mcmaster.ca accessed June 6, 2006.

Barillo, D. "Fire Fatality Study: Demographics of Fire Victims." *Presented at the American Burn Association.* Cincinnati, OH, March 1993.

Bastuji, H. "Event Related Potentials during Forced Awakening." *J. Sleep Res.* Vol. 12 (2003).

Berl, W. "Human Fatalities from Unwanted Fires." *US Dept. of Commerce.* NBS-GCR-79-168 (1978).

Bilwise, D. "Age Changes in Timing and 24 Hour Distribution of Self Reported Sleep." *The American Journal of the American Association for Geriatric Psychiatry.* Vol. 13, Issue 12 (2005).

Bonnett, M. , "Relationship of arousal threshold to sleep stage distribution and subjective estimates of depth and quality of sleep," *Sleep*, Vol. 1, Issue 3 (1978).

Bonnet, M. "The Threshold of Sleep: Perception of Sleep as a Function of Time Asleep and Auditory Threshold." *SLEEP.* Vol. 5, Issue 3 (1982).

Boselli, M. "Effect of Age on EEG Arousals in Normal Sleep." *SLEEP*. Vol. 21, No. 4 (1998).

Bowersox, S. "EEG Spindle Activity as a Function of Age: Relationship to Sleep Continuity." *Brain Research.* Vol. 334 (1985).

Bowman, J. "Waking Effectiveness of Visual Alerting Signals." *J. Rehabil Res Dev*. Volume 32 (1995).

Bregman, A.S. " Auditory Scene Analysis, The Perceptual Organization of Sound." MIT press, 2001.

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

Bruck D, and Horasan M. "Non-arousal and Non-action of Normal Sleepers in Response to a Smoke Detector Alarm". *Fire Safety Journal*. vol 25 (1995).

Bruck, D. "Non-awakening in Children in Response to a Smoke Detector Alarm." *Fire Safety Journal*. Vol. 32 (1999).

Bruck D. "The Who, Where and Why of Waking to Fire Alarms: A Review". *Fire Safety Journal*. vol 36 (2001).

Bruck D and Brennan P. "Recognition of Fire Cues During Sleep. Human Behavior in Fire: Understanding Human Behavior for Better Fire Safety Design." International Symposium, 2nd Proceedings (2001).

Bruck D, Reid S, Kouzma J, Ball M. "The Effectiveness of Different Alarms in Waking Sleeping Children". NFPA Standards Council Secretary (2004).

Bryan, J., Behavioral Response to Fire and Smoke. Chap. 3-12, The SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

Camets. "Glossary Definition, Sound Attenuation." http://ww.camets.com.au/info/glossary/soundatt.htm, Accessed March 2006.

Campbell, K. "Event Related Potential Measures of the Disruptive Effects of Trains of Auditory Stimuli During Waking and Sleeping States." *J. Sleep Research.* Vol. 14 (2005).

Canter, D. (Editor) *Fires and Human Behaviour: Second Edition,* David Fulton Publishers, England, 1990.

CDC, accessed October 31, 2005. http://www.cdc.gov/ncipc/factsheets/fire.htm

CDC Fact 1. "Fire Safe and Sound" U.S. Fire Administration. www.cdc.gov/ncipc.factsheets/fire.htm accessed January 2006

CDC Fact 2. "Special Populations Fire Safety Checklist" U.S. Fire Administration. www.cdc.gov/ncipc.factsheets/fire.htm accessed January 2006

CDC Fact 3. "Fire Safety Lasts a Lifetime." U.S. Fire Administration. www.cdc.gov/ncipc.factsheets/fire.htm accessed January 2006.

CDC Fact 4. "Let's Retire Fire." U.S. Fire Administration. www.cdc.gov/ncipc.factsheets/fire.htm accessed January 2006.

CDC. "Summary Health Statistics for U.S. Adults." US Dept. of Health and Human Services, 2004.

Chow, Shein-Chung. "Sample Size Calculations in Clinical Research." CRC Press, Florida, 2003.

Cicogna, P. "Slow Wave and REM Sleep Mentation." *Sleep Research Online.* Vol. 3, Issue 2 (2000).

Consumer Product Safety Commission. "A Review of the Sound Effectiveness of Residential Smoke Alarms," CPSC-ES-0502 (2004).

Cote, K. "The Role of the Spindle in Human Information Processing of High Intensity Stimuli during Sleep." *J. Sleep Research.* Vol. 9 (2000).

Cruickshanks, K. "Prevalence of Hearing Loss in Older Adults in Beaver Dam, Wisconsin." *American Journal of Epidemionology*, Vol. 148, No. 9 (1997).

Crowley, K. "An Examination of evoked K-complex Amplitude and Frequency of Occurrence in the Elderly." *J. Sleep Research.* Vol. 11 (2002).

Cunningham T. "And the Children Slept: An Independent Investigative study concerning reports of non-arousal by Children to Activated Smoke Detection Alarms and Related Research." U.S. Naval Academy Fire Department. (2002)

Diaz-Munoz, M. “Correlation Between Blood Adensoine Metabolism and Sleep in Humans.” *Sleep Research Online.* Vol. 2, Issue 2 (1999).

Duncan C. “The Effectiveness of the Domestic Smoke Alarm Signal.” Fire Engineering Research Report 99/5. (1999), ISSN 11734996, pp i – 83.

D’Souza, V. “Use of the Fire Dynamics Simulator to Predict Smoke Detector Activation,” Proceedings of the Fall Technical Meeting of the Eastern States Section of the Combustion Institute, Hilton Head, NC, December 2001.

Elder, A. “Fire Fatalities in Elderly People.” *Age and Ageing.* Vol. 25, No. 3 (1996).

Evans, M. Statistical Distributions, Wiley & Sons, NY, 2000.

Fahy R and Milos J. “Fatalities in Home Fires Where Smoke Alarms Operated. Proceedings” Human Behavior in Fire, Belfast. (2004), pp 57-66.

Fukuda, N. “Gender Differences in Slow Wave Sleep in Middle Aged and Elderly Subjects.” *Psychiatry and Clinical Neurosciences.* Vol. 53 (1999).

Grace, T. “Improving the Waking Effectiveness of Fire Alarms in Residential Areas.” Fire Engineering Research Report 97/13. (1997), ISSN 117345996, pp i – 90.

Gunn, P. “Frequency Weighting Networks.” Safetyline Institute, Government of Western Australia, 2005.

Halliwell, R and Sultan M. “A Method to Determine the Optimum Location for Fire Alarms in Residential Buildings.” Reprinted from Canadian Acoustics. vol 17 No. 2 (1989).

Hall, J. “Children Playing With Fire.” National Fire Protection Association. (2005).

Hall, R. “Stages of Sleep.” Web.umd.edu/psyworld/general/sleepstages. Accessed May 2006.

Harbison, J. “Sleep Disorders in Older People.” *Age and Ageing*. Vol. 31, Issue S2 (2002).

Hasofer, A. “A Stochastic Model for Time to Awaken in Response to a Fire Alarm.” *Journal of Fire Protection Engineering.* Vol. 11 (2001).

Henkel, G. “Sleep disorders in LTC.” *Caring for the ages*, Volume 4, Issue 1 (2003).

Hobbs, F. “The *Elderly Population*.” U.S. Census Bureau, Population Division and Housing and Household Economic Statistics Division, 2001.

ISO 8201. “Acoustics - Audible Emergency Evacuation Signal First Edition.” International Standards Organization, 1987.

Jin, T. “Studies on Human Behavior and Tenability in Fire Smoke.” Fire Safety Science – Proceedings of the Fifth International Symposium. (1997), pp 3 – 21.

Johnson, L. “Auditory Arousal Thresholds of Good Sleepers and Poor Sleepers with and without Flurazepam.” *SLEEP*. Vol. 1, Issue 3 (1979).

Kahn, M. “Detection Times to Fire-Related Stimuli by Sleeping Subjects,” National Bureau of Standards Center for Fire Research publication, NBS-GCR-83-435 (1983).

Kemp, L. “Personal Conversation.” April 1, 2006.

Kimura, M. “An animal model for pregnancy-associated sleep disorder.” *Psychiatry Clin Neurosci* Volume 52 (1998).

Kohsaka, M. “Effects of Bright Light Exposure on Heart Rate Variability during Sleep in Young Women.” *Psychiatry and Clinical Neurosciences.* Vol. 55 (2001).

Landolt, H. “Effect of Age on the Sleep EEG.” *Brain Research.* Vol. 738 (1996).

Lebon, O. “The First Night Effect may last more than One Night.” *Journal of Psychiatric Research,* Vol. 35, Issue 3 (2001).

Lee, A. “Possible Technologies for Improving the Audibility of Residential Smoke Alarms for Older Adults.” U.S. Consumer Product Safety Commission Directorate for Engineering Sciences. (2005), pp i – 34.

Lee, A. “A Review of the Sound Effectiveness of Residential Smoke Alarms.” U.S. Consumer Product Safety Commission Directorate for Engineering Sciences. (2004) (Revised), pp i – 35.

Levin, B.M. and Nelson, H.E. "Fire safety and Disabled Persons," *NFPA Journal*, v. 75, No. 5 (1981).

Lucas, J. "Summary Health Statistics for U.S. Adults," *Vital Health Statistics* 10 (218):5,34-37 (2004).

Loveridge R. "Fatalities From Fire in One and Two Family Residential Dwellings." Thesis. (1998), pp 393 – 399.

Lynch, J. "Nocturnal Olfactory Response to Smoke Odor." Executive Development. National Fire Academy. (1997).

ManPark, Y. "Age and Gender Difference in Habitual Sleep Wake Rhythm." *Psychiatry and Clinical Neurosciences.* Vol. 55 (2001).

Marshall, S. "Fatal Residential Fires: Who Dies and Who Survives?" *JAMA* , vol 279 No. 20 (1998).

Mallonee, S. "Surveillance and Prevention of Residential- Fire Injuries." Massachusetts Medical Society. , vol 335 No.1, pp 27 – 31 (1996).
Masako, T. "Examination of the First-Night Effect during the Sleep Onset Period." *Sleep*, Vol. 28, Issue 2 (2005).

McGwin, G. "Fire Fatalities in Older People." *JAGS*. Vol. 47 (1999).

Meacham, B.J. September-October 1999. "Integrating Human Behavior and Response Issues into Fire Safety Management of Facilities." *Facilities* Vol 17 Number 0/10, ISSN 0263-2772

Merck Manual of Geriatrics, Ch. 47. "Sleep Disorders." www.merck.com accessed May 17, 2006.

Miller, R. "Memory Consolidation and REM Sleep." Biology 202, Bryn Mawr College, 1998.

Nakano, M. "Experimental Study on Starting Time of Evacuation in Sleeping Condition." *AOAFST & JAFSE*. (2000) 4th proceedings, pp 236 – 274.

National Sleep Foundation. "Sleep and Aging." www.sleepfoundation.com/sleeplibrary. Accessed March 2006.

Nlcsafekids. "Fire Safety." www.nlcsafekids.org/firesafety, Accessed February 2005.

Nelder, J. "Generalized Linear Models." J Roy Stat Soc Ser A 1972: 135: 370-84.

Neubauer, D. "Sleep Problems in the Elderly." *American Family Physician.* Vol. 59, No. 9 (1999).

NFPA 72. "National Fire Alarm Code." National Fire Protection Association, 2002.

NHLBI. "National Sleep Disorders Research Plan." US Dept. of Health and Human Services, 2003.

Nicholas, C. "The Effects of Alcoholism on Auditory Evoked Potentials During Sleep." *J. Sleep Research.* Vol. 11 (2002).

Nicolas, A. "Sleep Spindle Characteristic in Healthy Subjects of Different Age Groups." *Clinical Neurophysiology.* Vol. 112 (2001).

Nober, H., Well, A., and Moss, S., "Smoke Alarms for the Hearing Impaired," *Fire Journal*, January/February (1990).

Nober, H. "Does Light Work as Well as Sound? Smoke Alarms for the Hearing-Impaired." *Fire Journal*, January/February (1990).

Nober, H. "Waking Effectiveness of Household Smoke and Fire Detection Devices." University of Massachusetts, Amherst, MA 01003. NBS Grant No. DA0001. U.S. Department of Commerce, National Bureau of Standards, Center for Fire Research. Washington, DC 20234. July 1983.

Page, M. "Human Body." DK Adult, NY, 2001.

Pedemonte, M. "Sleep and Wakefulness Auditory Processing." *Sleep Research Online.* Vol. 4, Issue 2 (2001).

Pezoldt, V. "Arousal From Sleep By Emergency Alarms: Implications From the Scientific Literature." National Bureau of Standards (1978), NBSIR 78-1484 (HEW), pp i– 31.

Pivak, R. "Sleep Spindles and Arousals: The Effects of Age and Sensory Stimulation." *Sleep Research Online.* Vol. 2, Issue 4 (1999).

Rechtschaffen, A. "Sleep and Dreaming." Principles of Neuroscience. McGraw-Hill, NY, 2000.

Richardson, Lee. National Fire Protection Association. Fire Alarm Evacuation—Are You Ready? Online Journal Exclusive. September 30, 2003.

Roby, R. "Phase SBIR I Report: A Smoke Detector Device for the Deaf. NIH Grant No. 1 R43 DC04254-01." Combustion Science and Engineering, Inc. 8940 Annapolis Road, Suite L. Columbia, MD 21045.

Roby, R. "Phase SBIR II Final Report: Smoke Detector Alert for the Deaf. NIH Grant No. 2R44 DC004254-2." Combustion Science and Engineering, Inc. 8940 Annapolis Road, Suite L. Columbia, MD 21045. May 28, 2005.

Rosenthal, L. "Auditory Awakenings Thresholds in Sleepy and Alert Individuals." *SLEEP*. Vol. 19, Issue 4 (1996).

Ross, M. "Smoke Alarms: What Consumers with Hearing Loss Should Know." <www.hearingloss.org.> September/October 2003.

Roehrs, T., "Sleep-Wake State and Memory Function." www.websciences.org/sleepandhealth/roehrs.html, accessed March 27, 2006.

Salzarulo, P. "Sleep Stages Preceding Spontaneous Awakenings in the Elderly." *Sleep Research Online."* Vol. 2, Issue 3 (1999).

Shannon, J. "Rude Awakenings: Smoke Alarm Conclusion Could Be Dead Wrong." NFPA Standards Council Secretary. (2002), pp 13 – 19.

Shapiro, C. "Impact and Epidemiology of Sleep Disorders." *BMJ.* Vol. 306 (1993).

"Sleep Stages", http://www.sleepdisorderchannel.net/stages, September 2004.

Tamura, R. "Comparing the Time to Response in Antidepressant Clinical Trials." Department of Statistics Class Notes, Purdue University, 2001.

Tijms, H. *Understanding Probability: Chance Rules in Everyday life*. Cambridge University Press. ISBN 0521833299 (2004).

Tsuji, Y. "Effects of Bright Light in the Morning on the Ultradian Rhythm at the Vigilance Level. *Sleep and Biological Rhythms.* Vol. 1 (2003).

UL Subject 1971. “Emergency Signaling Devices for use by the Hearing Impaired.” Underwriters’ Laboratory, 1991.

US Department of Commerce. “Profiles of General Demographic Characteristics.” U.S. Census Bureau, 2000.

Vasquez, J. “The Effects of Sensory Stimulation on REM Sleep Duration.” *SLEEP.* Vol. 21, No. 2 (1998).

“Fire Risks for the Deaf and Hard of Hearing.” Published by Tridata Corp, 1999.

Report From The UL Smoke Alarm STP Research Group on Childhood Awakening In Response To Smoke Alarms. UL Committee. pp 1 – 8.

Wong, L. “Minimum Fire Alarm Sound Pressure level for Elder Care Centers.” *Building and Environment.* Vol. 40 (2005).

www.wikipedia.org accessed January 2007.

Young, H. Statistical Treatment of Experimental Data. McGraw Hill, New York, 1962.

Zung W and Wilson W. “Response to Auditory Stimulation During Sleep; Discrimination and Arousal as Studied with Electroencephalography.” *Archives of General Psychiatry* vol 4 (1961).