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Waking Effectiveness of Audible, Visual and Vibratory Emergency Alarms on People of all Hearing Abilities

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Alerting devices of all kinds have been marketed to deaf and hard of hearing people as capable of providing levels of fire protection equal to what the audible alarm provides for people who are fully hearing able. This study, sponsored by the National Institute of Deafness and other Communication Disorders, quantified the effectiveness of commercially available devices by how well the alerting stimulus can awaken individuals of varying hearing abilities. Waking people from sleep is of significant importance because the majority of fire deaths (nearly 50%) occur between the hours of 11:00pm and 6:00am when most people are sleeping[1]. People recruited to participate in this sleep study were divided among three hearing classifications: profoundly deaf, hard of hearing, and fully hearing able. The alerting devices examined included a standard audible smoke detector (3100 Hz, >75 dB), a low frequency audible smoke detector (450 Hz, > 75dB), a strobe light (110 candela, 1Hz), a bed shaker, and an intermittent bed shaker (both 0.14-0.19 RSS). Sleep stage of the study participants was carefully monitored such that the impact of brain activity during sleep could be clearly distinguished in the study results. Sleep stage, hearing ability, device salience, age, and time to awaken were investigated in order to determine their influence on an individual's likelihood to arouse involuntarily.

Of the five distinct expressions of sleep, this study focused on three stages in particular: Stage 2, Delta, and REM. In Stage 2, the body temperature decreases, the heart rate slows, and the brain prepares for deep sleep. During Delta sleep, also know as Stages 3-4, brain activity slows making this the deepest stage of sleep. Stage 5 or REM sleep, also known as the dream stage, is characterized by an increase in brain activity to levels similar to the lightest sleep stage; however, the major voluntary muscle groups of the body remain paralyzed.[2] Over the course of a night's sleep, a person descends sequentially through Stages 1 through 4, then ascends back through the stages with REM replacing Stage 1 after the initial onset of sleep. The brain's traversal of the stages continues with the depth of each cycle lessening.[3] The duration of each stage is not equally distributed across each sleep period. In fact, Stage 4 occurs predominantly during the first third of the night, while REM is more prevalent during the last third[3]. An initial hypothesis of this study has been that the prevalence of fire deaths during the late evening hours may be related to the predominance of the deep sleep in

sleep patterns of adults who retire around midnight.

The experiment was designed such that the sample size of each hearing classification would be consistent with a binomial distribution (either success or failure in awakening) with success rates near or greater than 80%. Of the 111 subjects selected for the study, 32 were profoundly deaf, 45 were hard of hearing, and 34 were fully hearing able. Hearing classifications were based on analysis of participants' audiograms. People categorized as deaf had no hearing 90 dB or less over the sound frequency range of 500 Hz to 8000 Hz. Hard of hearing participants' average hearing ability fell between 20 dB – 90 dB over the range of 250 Hz – 8000 Hz. Fully hearing subjects had hearing of 20 dB or less across the frequency spectrum of 250 – 8000 Hz. The tests were conducted under controlled conditions at a nationally recognized sleep laboratory, Sleep Services of America. Individual alerting devices were activated at random for two minutes once subjects reached stable states within Stage 2, Delta, or REM sleep. Only three awakenings per subject were permitted. If arousal did not occur, additional devices were sequentially activated --with two-minute recovery intervals between activations-- until the subject awakened or experienced a vacillation in sleep depth. In this regard, multiple alarm activations could be achieved without violating the three awakenings per subject limit. Coherence upon awakening was determined by subjects' capacity to answer a series of simple questions. Study participants were not required to evacuate the facility upon alerting.

The percentage of standard audible smoke detector alarm activations yielding awakenings in hearing able subjects regardless of sleep stage was 92%. Hard of hearing and deaf subjects experienced awakening potentials with the same device of only 57% and 0% respectively. The low frequency alarm yielded better results for the hard of hearing, illuminating the impact of frequency on audibility; however, deaf subjects were still disadvantaged. Awakening potentials for the low frequency audible alarm were 11% for deaf subjects, 92% for hard of hearing, and 100% for hearing able.

The strobe's effectiveness was slightly elevated for the deaf, 57%, but poor overall with ratings of 34% for hard of hearing, and 32% for hearing able. These results clearly indicate that for people with hearing loss, strobes, though recommended by the National Fire Protection Association and the Americans with Disabilities Act, are not functionally equivalent to audible alarms.

The tactile bed shakers offered a much greater effectiveness for all of the hearing echelons in addition to demonstrating an awakening effectiveness for the deaf subjects equal to that of hearing able subjects exposed to audible alarms. Awakening effectiveness for the continuous bed shaker was 93% for deaf, 82% for hard of hearing, and 92% for hearing able subjects. The intermittent bed shaker provisioned 100% effectiveness for all study participants irregardless of hearing ability, underlining the fact that an intermittent tactile signal is sufficiently salient and recognizable as an emergency alarm, even more so than the continuous tactile alert. Weighting the device results according to the US population hearing demographics permitted a generalizing of the study results to the entire population.[4] A ranking of the devices based on this statistic is as follows: 100% for the intermittent bed shaker, 91% for the continuous bed shaker, 90% for the low frequency audible alarm, 83% for the standard audible alarm, and 33% for the strobe.

With one exception, the measured awakening effectiveness of the devices dropped when subjects were in Delta sleep. Only the intermittent bed shaker yielded equal, indeed 100% awakening effectiveness, across all sleep stages for people of all hearing abilities. Taking into account subjects' hearing levels and all of the

devices, awakening potentials were 59% in Delta, 65% in REM, and 69% in Stage 2. The variance in these data, however, is not sufficient to establish statistical significance to this phenomenon of fewer awakenings from Delta. The inability to grant statistical relevance to this despite experimental data has been demonstrated by other researchers[5, 6]. Nonetheless, it is apparent that there is a *trend* towards a decreased likelihood of awakening during the Delta sleep stage. And, the intermittent bed shaker's ability to evoke awakening equally across all sleep stages should not be ignored.

Other parameters found pertinent to awakening potentials were the age of study participants and the time to awaken. The intermittent bed shaker elicited responses among all test subjects for all presentations of the pulsed tactile signal. Of the other devices tested, study participants over the age of 60 alerted to 7% - 25% fewer alarm presentations than their 18 – 60 year old study counterparts. Expanding this statistic to the United States population in general, people over the age of 60 effectively awaken to 26-40% fewer alarms than younger people. Analysis of the latency period preceding awakening showed that 88% of the time, the subjects who awakened reached consciousness 30- seconds after the alarms were activated. 96% of the time, those who awakened reached consciousness after 60 seconds. Beyond 60-seconds, the chance of awakening dropped to 8%. In a similar set of experiments with audible alarms and fully hearing subjects, Bruck showed that 75% of awakenings occurred within 30 seconds of alarm activation, 87% occurred within 60 seconds, and the likelihood of awakening dropped to 13% after 60 seconds. In the field of fire safety, time to awaken is related to the amount of time one has to escape a building. If flames are spreading towards an alarm mounted along an escape route, a person may have only a limited amount of time after awakening to escape along that route before thermal conditions silence the alarm, and subsequently make exiting along that path impossible. Typically, audible smoke detectors degrade when the air immediately surrounding them reaches 92 C; and they are no longer able to produce sound at 114C [7]. Silencing of an alarm positioned adjacent to the fire's room of originated can occur within a minute during a typical house fire.

In conclusion, this study has served to provide a quantitative measure to the awakening effectiveness of the alerting devices commercially available for the deaf and hard of hearing populations. Strobes, promulgated by the National Fire Protection Association as functional equivalents to the audible smoke alarm, are actually 53% less effective than the standard smoke detector according to the weighted average rankings. The only devices equivalent to the audible detector for both deaf and hard of hearing people were the bed shakers, the intermittent bed shaker in particular. While sleep stage was not a definitive contributor to awakening potential, age was. This data has also shown that individuals of advanced age are at a greater risk of succumbing to fires at night because of their overall difficulty awakening. This is of particular importance because individuals over 65 compose the fastest growing portion of the population [8]. Combustion Science & Engineering, Inc. has leveraged this data to propose important recommendations to the National Fire Protection Association that will appear in the 2006 National Fire Code (NFPA 72) and Guide on Alternative Approaches to Life Safety (NFPA 101A) [9].

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

[2] " Sleep states" , http://www.sleepdisorderchannel.net/stages, September 2004.

[3] Pezoldt, V.J. and van Cott, H.O., " Arousal from Sleep by Emergency Alarms: Implications from the Scientific Literature," National Bureau of Standards Consumer Sciences Division publication, NBSIR 78-1484(HEW),1978.

[4] Lucas, J.W., Schiller, J.S. and Benson, V. " Summary Health Statistics for U.S. Adults" , Vital Health Statistics 10 (218):5, 34-37 (2004). According to the report, 83% of the United States population over 18 years of age is hearing able, 14% is hard of hearing, and 3% is profoundly deaf.

[5] Bruck, D. and Horasan, M., " Non-arousal and Non-action of Normal Sleepers in Response to a Smoke Detector Alarm," Fire Safety Journal, 25:125-139 (1995).

[6] Bonnett, M.H. and Johnson, L.C., " Relationship of arousal threshold to sleep stage distribution and subjective estimates of depth and quality of sleep," Sleep, 1:161-168 (1978).

[7] Experimental tests performed at Combustion Science & Engineering, Inc., Columbia, MD 2000-2002.

[8] U.S. Census Bureau 2004, " U.S. Interim Projections by Age Sex, Race and Hispanic Origin," http://www.census.gov/ipc/www/usinterimproj/, September 2004.

[9] Recommendations based on information generated from this study will appear in NFPA 72: Appendix 11.3.6, and NFPA 101A: 6.4.6.3