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Waking effectiveness of visual alerting signals

Sherry K. Bowman, MClSc; Donald G. Jamieson, PhD; Robert D. Ogilvie, PhD
Hearing Health Care Research Unit, The University of Western Ontario, London, ON N6G 1H1 Canada; Department of Psychology (Sleep Lab), Brock University, St. Catharines, ON L2S 3A1 Canada

Abstract—People who are unable to hear acoustic alarm signals because they have a complete or partial hearing loss must rely on visual or tactile signals to warn them in the event of an emergency. However, consumers report that personal smoke detector devices which provide a visual alarm do not wake people reliably. We examined the ability of visual alerting devices to wake people from the deepest stages of sleep: slow wave sleep (SWS) and rapid-eye-movement sleep (REM). These results were related to the physical (optical) characteristics of devices currently on the market. In Experiment 1, a range of strobe intensities and locations were investigated. Experiment 2 confirmed the results of this pilot study on an independent set of subjects. On each trial, the strobe was allowed to run at a constant intensity until the subject awoke, or a maximum of 5 min had elapsed. Even though a diffuse light remained directly over the subject's face for each trial, subjects did not wake consistently. Under the favorable optical (smoke-free) conditions of the present study, the most intense of the devices presently offered for sale in Canada cannot be relied on to wake a sleeping person in the event of a fire. It remains unclear whether any visual alerting device can be expected to safely wake a sleeper in an emergency situation.

Key words: *deafness, hearing loss, sleep arousal, smoke detector alarms, visual arousal thresholds.*

INTRODUCTION

Every year, 80,000 Americans die or are injured in fires. Most fatal fires occur at night when the victims are asleep (1). A study of multiple death fires indicated that more than 80 percent of them occur between 8:00 p.m. and 8:00 a.m., with the largest number (40.5 percent) between midnight and 4:00 a.m. (2). These considerations make smoke alarms an important part of fire safety planning.

In approximately 95 percent of fire incidents, serious injury or death is prevented by use of a fire safety alarm (1). There are three primary options for alerting the sleeper in the event of an emergency: auditory, tactile (vibrational devices, or fans), and visual. While emergency and warning signals are commonly acoustic, these are not appropriate for persons who are deaf or hearing impaired. Approximately 8 percent of the North American population is hard of hearing, having serious difficulty perceiving acoustic signals and alarms when not wearing amplification (3). An additional number will have significantly reduced ability to hear such signals and alarms due to a partial hearing loss.

The most common alternative to acoustic alarms is a visual alarm. However, deaf and hard-of-hearing consumers report that the strobes typically used in family dwellings cannot be relied upon to alert them in the event of an emergency.[1] Manufacturers, however, feel that the needs of consumers are being met. A recent study by Nober et al. (4) suggests that deaf people receive about the same levels of protection from strong visual smoke alarm strobe signals as hearing persons receive from audible smoke alarms: in their study, 90 percent of the deaf subjects were awakened by strobe devices. Unfortunately, these results are inconclusive because (*a*) they did not control for the stage of

Address all correspondence and requests for reprints to: Donald G. Jamieson, PhD, Hearing Health Care Research Unit, The University of Western Ontario, Elborn College, Room 2300, London, ON N6G 1H1 Canada.

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[1] Personal communication with J. Beattie, January 1992.

sleep during which the stimulus was presented, and (*b*) they relied on self-report measures as to whether the subjects were awakened by the flash unit or by another member of the household. There remains, therefore, a clear need to assess the effectiveness of smoke detector systems that provide a visual alarm.

Underwriter's Laboratories (UL) has undertaken research relating to standards for fire emergency signalling to alert people who are hard of hearing. One part of this study was designed to assess performance with a flashing strobe in an otherwise dark room. The study demonstrated that some subjects were temporarily blinded, or sufficiently disoriented by the flashing light that they failed to complete even simple tasks (5).

In a nighttime bedroom study (home or school dormitory), deaf persons were alerted with a strobe device which operated for 4 min and then shut off (5). The chosen time frame corresponded to the minimum alarm duration specified by UL for battery operated smoke detectors. A flash repetition rate of 1 Hz was used, since slower rates, presented in a dark room, have lead to disorientation and confusion. The alarms were activated randomly between 1 a.m. and 4 a.m. If the subject woke up, he or she recorded the time of waking, which was later compared to the initiation time of the alarm. The intensity of the strobe was adjusted up or down depending on its effectiveness, until a threshold point of detection was located. It was reported that 92 percent of test subjects (not using medication) were alerted by a strobe light that was 110 candela (cd), while subjects using medication were awakened only 28 percent of the time.

Whether or not such an alarm can wake a person reliably is not clear (6). Moreover, it is clear that any such alarm must act quickly: once a flame has entered the room, a fire can engulf the entire room in as little as 2 min. Carbon monoxide can build up during a fire and enter the blood stream, causing persons to become disoriented (3). Such considerations emphasize the need for effective systems to warn hard-of-hearing and deaf persons of the presence of a fire. Visual alarms, such as flashing lights, however, may be ineffective since they may be out of the field of vision, or the user may be asleep. For hearing people, single unit audible alarms are typically mounted outside the sleeping area. For deaf or hard-of-hearing people, a single alarm would need to be placed inside the sleeping area, so that smoke must enter the bedroom before the smoke alarm signal is triggered. These considerations underline the need for a reliable, fast-acting alarm system.

An alternative to acoustic or visual alarms is to use a tactile signal (7), such as a signal-activated vibrator (placed between the mattress and box spring or under a pillow). Such devices are reported to be effective at alerting sleepers, but vibration devices have not been approved as safety devices (3), and some vibratory devices must be worn and may, therefore, be easily forgotten. Consequently, vibratory devices may be a less suitable choice for alerting persons in emergency situations.

Canadian Standards

At present, there are no known standards or codes relating to the use of nonauditory alarm systems in Canada. Neither the Canadian Building Code nor the Fire Code addresses the problem of sleep arousal. A task group has been formed under the Standing Committee on Occupancy for the National Building Code to look into the issues regarding fire alarms, including the problem of arousal from sleep; however, their mandate is restricted to audible alarms only.[2] Moreover, the available international standards define criteria applicable only to the recognition of audible signals (8,9).

American Standards

In the United States, several codes address smoke detectors, but do not include specifications for visual signals from these detectors (10). The Americans with Disabilities Act (ADA) (11) provides comprehensive civil rights protection to "individuals with disabilities in the areas of employment, public accommodations, state and local government services, and telecommunications." The *Federal Register* (Section 4.28), states minimum photometric standards for visual alerting devices to be "white xenon strobe or equivalent, intensity (75 cd), flash rate (1–3 Hz), pulse duration (0.2 s), and location features. However, a higher level (110 cd) may be required to alert sleeping persons (Section A4.28). UL upgraded this standard to a minimum of 177 cd; however, this has not been legislated within the ADA.[3] Devices with the 177 cd rating are said to be authorized to be labelled as "smoke detector for the hearing impaired."[4]

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[2] Personal communication with R.E. Halliwell, March 1992.

[3] Personal communication with L. Johansen, Accessibility Specialist, Office of the Americans with Disabilities Act, December 21, 1993.

[4] Personal communication with D. Parsons, Manufacturing and Marketing, Ven-Tek, Inc., September 24, 1993.

Visual Smoke Detectors on the Market

Manufacturers offer a wide range of intensity levels on their strobe signals ranging from 1.5 to 117 cd (Wheelock Inc.) and 120 cd (Gentex Corporation), with such features as audible signals offered as options. Hard-wired systems (smoke detector, transmitter, and alerting device) are available along with the portable option. Warnings have been placed on specification sheets for these lower-intensity devices so that people are aware of the fact that "the intensity of the strobe may not be adequate to alert or awaken occupants in the protected area" (12). Manufacturers, however, are discontinuing many of these devices and replacing them with devices which meet the latest standards. The first manufacturer to meet the 1992 UL requirements was Ven-Tek. Accordingly, the specifications for this device read "smoke detector for the hearing impaired." This device is available as a portable or hard-wired device, 180 cd, with a flash rate of 65–75 cycles/min.

Description of Sleep and Wakefulness

Standard polysomnographic criteria for sleep and wakefulness are defined in Rechtschaffen and Kales (13). Quiet and active sleep can be defined further with respect to these criteria.

Quiet sleep, synchronized, slow-wave-sleep (SWS) or non-rapid-eye-movement (NREM) sleep, has an EEG characterized by high-voltage waves with slow frequencies. Neck and chin electromyograms (EMG) indicate a reduced but apparent muscle tone. There are four substages of quiet sleep in humans (14). Nober, Peirce and Well (15) claim that SWS and rapid-eye-movement (REM) sleep stages alternate, with REM recurring about every 90–110 min during sleep. Remmers (14) described Stage 1 as characterized by a loss of alpha waves; Stage 2 is denoted by the presence of sleep spindles and K-complexes; Stage 3 is marked by high-amplitude delta activity; and Stage 4 contains more than 50 percent delta activity.

Active sleep (desynchronized, paradoxical, or REM sleep is accompanied by low-voltage, mixed frequency EEG tracing, intermittent REMs and a sustained suppression of neck and chin EMG tracing. Muscle twitching, fluctuations in penile tumescence, and loss of deep tendon reflexes are also characteristic of this stage (14). In addition, rhythmic contractions of the middle ear muscles have been noted (16, 17). Essentially, REM sleep is a stage of heightened EEG activity which recurs every 90–110 min (18). During REM sleep we are almost completely paralyzed. Only the heart, diaphragm, eye, ear, and smooth muscles are spared from this paralyzing effect (19).

Sleep researchers distinguish the tonic and phasic events of REM (20). Molinari and Foulkes (21) proposed a two-factor model of stage-REM based on presumptive support at the psychological level. It is their contention that "periods" of stage REM are unified in their tonic dimensions but phasically heterogeneous. Phasic events occur in conjunction with intense central excitation and are associated with decreased responsiveness to afferent stimulation. This was demonstrated by consistently smaller auditory evoked responses (AER) during bursts of ocular activity (22). Much of the dreamlike nature of stage-REM mentation derives from "phasic activation" in stage REM. Molinari and Foulkes (21) postulated that nonphasic REM may be similar to episodes of NREM sleep, and the phasic activation of stage REM may not be entirely limited to that stage. They suggest that this tonic-phasic distinction provides a means for recognizing important intra-REM variations and similarities as well as differences between stage REM and other sleep stages.

In an entire night, 4–6 REM periods are expected to occur variably across subjects (23), beginning after one or two hours of NREM sleep (24). REM phases become progressively longer toward morning. Conversely, NREM occurs more frequently and is deeper in the early part of the night and becomes shallower and shorter toward morning (25). Thus, it was proposed that the length of the REM period confounds the analysis of early versus late REM trials (26), making it difficult to discern how length of the REM period relates to the awakening threshold.

Arousal During Sleep

The ease with which people can be awakened varies as a function of stage of sleep (15). In Stage 1, people are easily awakened by noise or a voice. During Stage 2, the person is sound asleep but is still easily awakened. In Stage 3, an intense stimulus is required to awaken a person, while irrelevant stimuli do not disturb sleep. Finally, Stage 4 requires even more intense stimuli to awaken a person, and once awakened the person becomes alert slowly. Rechtschaffen et al. (26) reported that the threshold of arousal increases from the first to the second phase, but there was no significant difference between arousal thresholds during phases 2, 3, and 4. Zung and Wilson (27) contended that in the deepest or "E" stage of sleep, discriminative ability is present but reduced compared to other stages of sleep.

Remmers (14) contends that sleep moves in an orderly sequence from Stages 1 to 4 of quiet sleep and in doing so progresses to increasingly deeper sleep. Sleep stages are distributed differentially over the night such that there is more time spent in SWS early in the night, and more time spent in REM in the later half of the night.

The presence of alpha waves is associated with momentary arousals. Alpha increases and behavioral responses combine to identify microarousals from sleep with increased precision (28). Less alpha occurs in the second half of the night. Both of these may allow the subject to be physiologically aroused more easily in the first half of the night (29). During the night, cumulative REM as a percentage of total sleep time gradually increases from 3 percent during the first hour to 24 percent by the seventh hour. Cumulative total SWS decreases from 55 percent to 22 percent during the night (30). Thus, SW activity declines over time (31). Stage 1 sleep remains nearly constant across the night at 5 percent. Stage 2 is nearly constant after the second hour at 49 percent. The average sleeper awakens 8 or 9 times in a night, for at least 15 sec, and awakens 80 times a night for at least 2 sec (32). These arousals are usually accompanied by increases in alpha activity; arousals lasting less than 1–2 min are seldom recalled in the morning.

Research using painful electrical stimuli demonstrated that the threshold of arousal from sleep varies during the night, within a single phase of sleep (33). The most stimulation was required to awaken people in Stages 3 and 4. With olfactory stimuli, behavioral and EEG arousals were elicited more frequently in Stage 2 than in REM sleep or Stage 4 sleep (34). In Stage 4, the threshold for auditory smoke alarms ranges from 60–120 dB (35). Smoke alarms produce an 85 dB signal, with an additional loss of approximately 15 dB by passage through a closed door. Therefore, it is questionable whether an auditory alarm would awaken hearing persons in all stages of sleep.

In general, people are difficult to awaken from REM sleep (19). The unprovoked arousal from REM sleep is comparable to Stages 1 and 2 (NREM sleep), while arousal from SWS occurs less frequently (36).

Rechtschaffen et al. (26) claim that the waking threshold decreases as the amount of accumulated sleep increases. When split into 3.5 hour divisions, waking was more frequent during late REM trials than during early REM trials. Waking thresholds were similar for REM periods and Stage 2, but both had lower waking thresholds than delta sleep.

In contrast, Badia, Wesensten, and Lammers (37) reported that subjects were less responsive to olfactory stimuli during the last third of the night than in the early or middle parts of the night. Johnson et al. (38) reported that in the early morning, average arousal threshold was highest in Stage 4, and lowest in either Stage 2 or REM sleep. With no consistent differences between Stage 2 and REM, good and poor sleepers did not differ in arousal threshold, regardless of sleep stage.

Nober et al. (15) reported the arousal was not a function of gender, time of night, or day of the week and Rechtschaffen et al. (26) found no general systematic relation to waking threshold with body temperature, respiratory rate, heart rate, or skin resistance. Wilson and Zung (39) reported that women were more easily aroused from sleep than men by neutral nonmotivating auditory stimuli, although arousal threshold to significant sounds did not differ. Meaningful auditory stimuli were not differentially effective across sleep stages, although auditory awakening thresholds tended to be higher during Stage 4 sleep (40).

Previous studies concerning the effects of sleep laboratory adaptation noted that when normal subjects spent two nights in the sleep laboratory, there were significant changes noted on the second night of the study. Specifically, it was noted that 1) the amount of time spent "awake" and "drowsy" decreased; 2) time spent in Stage 3 increased; 3) the latency to the first REM period and the first Stage 3 sleep period were reduced; and 4) the number of REM periods increased slightly on the second night (41).

Central Processes

Wilson and Zung (39) claim that three central processes underlie arousal from sleep:

1. the stimulus must be received by the appropriate sensory organ passed to the cerebral cortex;
2. the stimulus must be analyzed by the cerebral cortex for importance and content;
3. if the stimuli are personally significant, corticofugal impulses are sent back to the reticular formation, which in turn may evoke arousal.

Rechtschaffen et al. (26) suggested that signals can be detected without waking if the response is incorporated into a dream. Incorporation of stimuli into dreams may be a concern when signals are presented below waking intensity and gradually increased, increasing waking thresholds during REM periods. During NREM sleep, K-complexes can be observed in EEG recordings in response to external

stimuli, indicating that the stimulus registered without observable behavioral or alerting responses on EEG activity. But, Salisbury and Squires (42) conclude that data are insufficient to determine whether K-complexes reflect arousal and desynchronizing mechanisms or antiarousal and oscillation enhancement mechanisms.

Visual Alarm Signal Specifications

Color

Nober et al. (1) recommended that white strobe flashes be used in visual alarm systems for waking people.

Temporal Pattern

In standardized audible warning signals, the International Organization for Standardization specified a "three-pulse" temporal pattern, consisting of an "on" phase of 0.5 sec ± 10 percent, sounded for three successive "on" periods, followed by an "off" phase lasting 1.5 s ± 10 percent (9). It is not known whether these patterns could be generalized to visual and tactile signals to aid those who are hearing impaired and/or work in intense background noise where acoustic warnings are inaudible.

Rate

UL (43) recently published standards for signalling devices for the hearing impaired. One requirement is that the strobe signal flash at a rate between 1 and 3 Hz. A task force has recommended that the ANSI-1980 standard be modified so that flashing lights for visual alarms operate at approximately 1 Hz (10). Higher rates of flashing may induce epileptic seizures, with effective flash rates reported to be 8–20 Hz or 10–25 Hz (44,45). Such photosensitivity is greatest between 5–24 years of age (1 in 4000), but has also been reported in infants and the elderly (46). A separate manufacturing and consumer concern is that higher flash rates decrease the life of the bulb.

Intensity

If the mounting height is within 24 in (61 cm) of the ceiling, and the detector and signalling device are in the same room, the intensity of the signal, required by UL (43), is 177 cd. If the signal is placed more than 24 in (61 cm) from the ceiling, the required intensity is 110 cd. It is not clear on what basis these standards have been developed.

Location

Placement of a visual strobe near the ceiling may be obscured by smoke (10). The strobe light may be more effective if placed near the floor, since this location will not be obscured by dense smoke and gases rising in a room (10).

Duration

According to Bleck (47), both pulse duration and rate influence the perceived brightness of photic pulses. In a study of the brightness of photic pulses which varied in pulse duration and separation, Bleck and Craig (48) found that two pulses separated by 0.02 sec were always perceived as one, and were always perceived as two when separated by 0.04 sec. Maximum brightness occurs for pulses of duration 75 ms to 100 ms.

METHODS

The present study was designed to evaluate the efficacy of currently available, personal smoke detector systems and to identify the parameters of a visual signal which would consistently wake a person from the deepest stages of sleep. Sleep stage was monitored electrophysiologically so that the likelihood of waking in time for safe evacuation in the event of fire, given a specific warning signal, could be determined. Safe evacuation was determined on the basis of the British fire safety code, which designates 2.5 min as the safe evacuation period after discovery (1).

Two experiments were conducted. In addition, the physical characteristics of visual alerting devices currently on the market were measured by an independent testing laboratory and compared to those used in testing. Experiment 1 evaluated the experimental manipulation, including the characteristics of the light source to be tested. Experiment 2 studied the relation between visual signals, sleep stage, and waking in greater detail.

Behavioral testing was conducted in a "state-of-the-art" sleep laboratory. All-night sleep was monitored to ensure that subjects were in periods of SWS and REM sleep prior to the presentation of the visual alerting signals. Strobe flashes of varying intensity were then presented to determine the threshold for waking.

Experiment 1

Approach

This study used the method of ascending limits (gradually increasing light intensity) to explore various aspects of the testing procedure and to obtain initial information relating sleep stage, visual signals, and waking probability. A strobe with a pulse rate of 1 Hz was turned

on at a "low" level after at least 5 min of SWS or REM sleep. Intensity levels varied across trials, as the initial objective was to find an intensity level which would awaken a sleeper within 2.5 min, in accordance with the British fire safety code. Light levels were altered by adjusting the light source in four steps. In the absence of arousal, presentation duration varied between 20 sec and 150 sec.

During subsequent SWS or REM periods, the procedure was repeated, beginning with the strobe at a level which was two steps below the lowest level to which the subject had previously responded. The level was then increased in fixed increments. This procedure was repeated in an attempt to study one SWS trial and one REM trial both early in the night and late in the night, yielding a maximum of four arousals. Sleep stage could not be controlled precisely because in the natural sleep cycle certain stages occur more frequently at different times of night (**Table 1**). Subjects were not asked to evacuate as in previous studies, because electrodes were applied to the scalp so that sleep stages could be monitored. Threshold was defined as the level at which the subjects awoke (opened their eyes and sat up in bed).

It was felt that disruption of sleep beyond four arousals might have an adverse effect on our subjects, and could be too artificial to permit our study to be representative of real-life behavior.

Subjects

Seven young normal hearing women, 18 years or older, were recruited for the first experiment. These subjects had no history of eye disease or epilepsy. All reported that they were "good sleepers" and had normal hearing as confirmed by a test measuring thresholds at octave intervals between 250 Hz and 4000 Hz.

The subjects were recruited through advertisements and posters. An honorarium of 15 dollars was provided for participation in the study. All subjects toured the sleep laboratory and received instructions about the experiment procedure before signing a consent form to participate.

Apparatus

Testing occurred in a 3m × 3m, sound-attenuated, electronically shielded room, illuminated by a red filtered 40 W light source, to minimize intrusiveness. The room was equipped with a single bed, dresser, mirror, closet, and night table. A white strobe flash of variable intensities was mounted above and within 10 ft (3 m) of the sleeper's pillow to provide a diffuse distribution of light regardless of which side the head was facing when the flash was activated. This distance and position helped to ensure constant luminosity at the eye, unless the subject was lying face down (4). **Figure 1** provides a schematic diagram of the laboratory, including the sleep chamber and control room.

Electrophysiological measures were obtained using a 14-channel electroencephalograph (Nihon Kohden model 4314B), digitized, and stored on-line using the Microcomputer Quantitative Electrophysiology acquisition and anal-

Table 1.
Ratio of arousals to trials for individual subjects in Experiment 1.

Subject	Light Position	Distance to Pillow	Flash Rate	Ratio of Arousals SWS	Ratio of Arousals REM
1	F/B	180 cm	3 Hz	0/2	1/2
2	F/B	180 cm	3 Hz	0/0	4/4
3	F/B	180 cm	1 Hz	1/3	1/1
4	F/B	180 cm	1 Hz	0/2	1/2
5	F/B	180 cm	1 Hz	0/2	1/2
6	O/F	144 cm	1 Hz	0/2	1/2
7	O/F	75 cm	1 Hz	0/1	2/3

F/B = foot of bed; O/F = directly over face; SWS = slow wave sleep; REM = rapid eye movement sleep

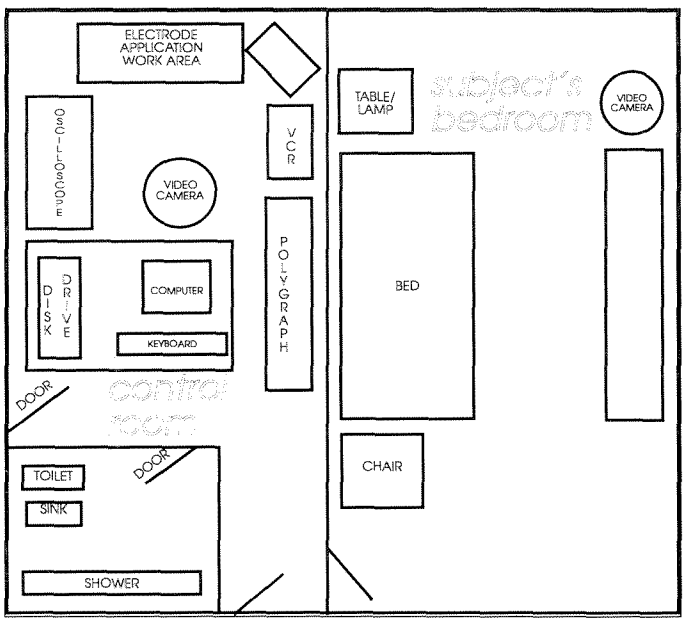

Figure 1.
Schematic diagram of behavioral testing laboratory, showing location of sleeper, experimenter, warning signal, and monitoring equipment.

ysis program (MQE). Data were archived using a Maximum Storage optical disk drive (model APX-5200) and an 8-channel FM tape recorder (Vetter, model D). The EEG data were also monitored using a 20 MHz oscilloscope (Hameg). A Sony Trinitron monitor with a Splitter/Inserter (RCA model TC147OA) and two RCA CCTV low illumination video cameras were used to monitor/videotape the subject and physiological measures simultaneously. These tapes can later be used to review sleeping positions during presentation of the flashes as well as the waking responses. An audiometer (Beltone) was used to screen hearing. A sound level meter (Bruel and Kjaer) was used to monitor the noise level in the subject's bedroom. Communication between the control room and the sleep room was maintained by an intercom system. The temperature of the sleep room was recorded at night and in the morning of a sleep session.

Procedures

Before taking part in the study, the subjects were asked to attend an orientation session where a demonstration of the sleeping session took place and consent forms were signed. The hearing test was then given. Subjects were asked to refrain from drinking caffeine after supper, drinking alcohol, or taking daytime naps on their scheduled day in the sleep laboratory.

Subjects were asked to arrive at the sleep laboratory about one hour before their normal bedtime to complete a pre-sleep questionnaire to assess daytime activities, and to have the electrodes attached. The criteria of Rechtschaffen and Kales (13) were used as a guideline for sleep recordings. One bipolar submental electromyographic (EMG) channel, and two horizontal electro-oculographic (EOG)—left and right outer canthus, each referred to A2—channels were used.

Silver disk electrodes filled with electrode cream were secured with Micropore surgical tape or collodion-soaked gauze (EEG placements) in order to record electrophysiological measures. Inter-electrode impedances were maintained below 5 K. A high-cut filter setting of 35 Hz and a time constant of 0.3 were used to process the EEG and EOG.

Once the subject had retired to bed, the researcher read the following instructions on the nature of the experiment and their laboratory duties:

> This is a study to test the effectiveness of visual fire-alerting devices during various stages of sleep. Once you are sleeping a flashing light will be presented. If this was an alerting device in your own home, assume that there could be smoke, flames, or heat in your room. Your only concern is evacuating your room as quickly as possible. Since these data will be extremely important in establishing guidelines for manufacturers of alerting devices for the deaf/hearing impaired, it is imperative that you get ready to evacuate as soon as you detect the signal. As soon as you detect the flashing signal, please sit up in bed and put your feet on the floor. Once this is complete you will be asked to lay back down to sleep again. Be careful not to pull the electrodes out since we will be monitoring and presenting the signals during different stages of sleep.

Subjects were also told that an award of 15 dollars would be offered to the person who, at the end of the study, had put her feet on the floor the fastest after the strobe had been flashed.

Once instructions had been given and the equipment calibrated, the sleep session began. To discern whether the light was being incorporated into the subject's dreams, when subjects were awakened by the strobe flash, they were asked what their last sleeping thoughts were. Each subject spent one night in the sleep lab. The location of the light was varied according to the results obtained with previous subjects. Including the first subject, who was tested to confirm that the equipment was operating correctly and to test the protocol, the first five subjects were tested with the light on the ceiling at the foot of the bed (i.e, in a typical position for a smoke detector). Next, one subject was tested with the light directly overhead on the ceiling. The final subject was tested with the light suspended over her face, since previous locations had been found to be ineffective.

The intensity of the strobe was increased in 30 sec increments until the subject awoke. If the subject failed to respond to the signal within 5 min, she was awakened via intercom, to avoid rewarding her for remaining asleep. Upon waking in the morning, subjects were asked to complete a post-sleep questionnaire to obtain a qualitative report of their night's sleep. Electrodes were removed and the subject was offered juice, coffee, and a snack, as well as the use of shower facilities.

Results

Table 1 summarizes the conditions and overall results of testing with individual subjects. The two columns on the right of the table report the ratio of successful wakings to trials, within SWS and REM sleep. It is clear that visual signals did not reliably wake subjects in any sleep stage, and that many subjects did not awaken even when the highest intensity levels were presented. It was therefore

decided that only the highest intensity levels available would be used during the second phase of this study and that all testing would occur with the light source directly over the face.

Experiment 2

Subjects

Thirteen women, age 18 and older, were recruited. None had a history of eye disease or epilepsy, and all were self-reported "good sleepers."

Procedure

Experiment 2 used the highest light intensity levels, presented close to the subject's pillow (75 cm) to ensure a bright and diffuse distribution of light on the face, regardless of sleeping position.

For each subject, one intensity of a strobe flash was selected for presentation once each during four test intervals: one early (before 3 a.m.) and one late (after 3 a.m.) stage of SWS and REM sleep, respectively. It was not always possible to do this, because in normal sleep cycles, SWS sleep tends to occur during the early part of the night and proportionally more time is spent in REM later in the night (**Table 2**). Signal intensity was initiated at 7.6 Lux on the first trial, and raised to 19.9 Lux on subsequent trials if the subject did not awake. The light was allowed to flash for an extended period of time (maximum of 5 min) on each trial, and the elapsed time to waking was noted. If waking had not occurred within 5 min, the light was considered ineffective for that trial.

On some trials, testing began with the 7.6 Lux; if the subject did not awaken within 5 min, the higher level stimulus was presented after a 2-min interval for a maximum allowable time of 5 min. If the subject remained asleep on the second trial, the intercom was used to awaken her, so as not to reward her for remaining asleep. This procedure provided a reasonable opportunity to wake the subject within an interval of time which would permit safe evacuation in the event of a real fire.

Behavioral data recorded included the date, subject number, night number, trial number, time, stage of sleep, tonic/phasic events, intensity of light, length of time for presentation of light, head/body position, and whether arousal had occurred. The time of sleep onset and thus test initiation was highly variable across subjects. Over 38[5] trials, the mean time between lights out and arousal varied between 18 and 263 min (mean = 89 min; SD = 66 min).

Results

Analysis: An arousal was recorded each time the subject awakened during light presentation. A nonarousal was recorded for each failure to respond to the light. The proportion of arousals was computed for each intensity level, and for each stage. **Table 2** summarizes test condi-

[5] Note that one subject had only two intervals averaged into the mean time between arousals (not three).

Table 2.
Summary of test conditions (sleep stage and light setting) and behavioral outcome for each trial in Experiment 2.

	Trial				
Subject	**1**	**2**	**3**	**4**	**5**
s1	SWS (8) FR	R/2 (8) FR	SWS (16) FR	*REM (16) FR	—
s2	SWS (8) FR	SWS (16) 0:10	REM (8) 2:07	—	—
s3	SWS (8) FR	REM (8) 1:39	SWS (16) FR	2 (8) FR	—
s4	SWS (8) FR	SWS (16) 0:13	REM (8) 0:10	REM (8) 0:14	—
s5	SWS (8) FR	SWS (16) FR	REM (8) FR	REM (16) FR	—
s6	SWS (8) FR	SWS (16) 0:07	REM (8) FR	REM (16) 3:38	—
s7	REM (8) 0:12	SWS (8/16) FR/1:06	REM (8/16) FR/3:26	—	—
s8	SWS (8/16) FR/FR	REM (8) 0:04	REM (8/16) FR/2:00	SWS (16) 4:00	—
s9	SWS (8/16) FR/FR	SWS (16) FR	REM (16) 0:05	REM (8/16) FR/0:04	—
s10	SWS (8/16) FR/FR	SWS (16) 0:10	*REM (8/16) FR/4:00	2 (16) FR	—
s11	SWS (8/16) FR/FR	REM (8) 0:02	2 (8/16) FR/2:59	REM (16) FR	—
s12	SWS (8/16) FR/FR	REM (8) 0:02	*REM (8) FR	SWS (16) FR	REM (8) 0:04
s13	SWS (8/16) FR/FR	REM (8/16) FR/FR	REM (16) FR	REM (16) FR	—

Note: Sleep stage is coded as SWS (slow wave sleep), REM (rapid eye movement sleep), 2 (Stage 2 sleep), or R/2 (mixed sleep stage) [* indicated where a stage change occurred during trial]; light level is setting of controller of light (8 μF or 16 μF) with 8/16 representing an advancement to higher intensity after a 2 min pause; behavioral outcome is coded as FR (failed to respond) or as the time from signal onset to arousal in minutes:seconds (maximum 5:00).

tions and behavioral outcome for each subject for each trial. In the table, "FR" indicates that the subject failed to respond within the 5 min time limit. Where times are given, the sleeper did awaken in the time indicated.

Probability of Arousal: Data were collapsed across subjects and trials, to determine the probability of waking from each sleep stage, as a function of light intensity. **Figure 2** displays how the cumulative probability of arousal increased overtime as the light flashed at a particular intensity level. Even over the full 5-min trial, *no* subject was awakened from SWS by the 7.6 Lux light, and waking occurred from SWS fewer than 30 percent of the trials with the 19.9 Lux level. Subjects were awakened from REM sleep approximately 50 percent of the time during the 5-min trial, with the overall proportion being almost identical for the two light intensities.

In all conditions, waking tended to occur soon after light onset or not at all: even at the highest intensity of light, a 30-fold increase in time for the light being on (from 15 sec to 5 min), only doubled the probability of arousal. However, the largest proportion of subjects failed to respond even after a full 5 min.

The proportions occurring with 2.5 min and 5 min of signal onset area is summarized in **Table 3.** Clearly, subjects did not wake consistently to the flashing signal at any sleep stage, or light intensity level. The overall probability of arousal within 2.5 min was only 27 percent. Doubling the time interval to 5 min increased the probability of waking by only 8 percent to a still unsatisfactory 35 percent, across conditions.

Sleep stage did affect probability of arousal, [$\chi^2(1,59) = 4.39$, $p < 0.05$] for the 2.5 min limit and [$\chi^2(1,59) = 5.26$, $p < 0.05$], indicating that arousal was more frequent from REM sleep than from SWS.

During REM sleep, there were no significant differences between the number of arousals at the two intensity levels presented (8 μF/16μF). During SWS however, arousal was significantly more frequent at the 16 μF intensity level [$\chi^2(1,30) = 5.74$, $p < 0.05$] and [$\chi^2(1,59) = 4.59$, $p < 0.05$] for the 5 min and 2.5 min criteria, respectively.

Intensity level did affect probability of arousal during SWS [$t(12) = 2.73$; $p < 0.05$; m = 300.0, $M_{16} = 201.6$]; there was no difference during REM sleep. This result may be due to the fact that many REM-16 trials were conducted following 5 min of REM-8 *during which waking did not occur:* thus, waking in the REM-16 condition may reflect some cumulative effect of the REM-16 condition with the preceding REM-8 condition. At the lowest intensity level sleep stage (SWS/REM) affected probability of arousal [$t(12) = -3.46$, $M_{REM} = 188$, $M_{SWS} = 300$].

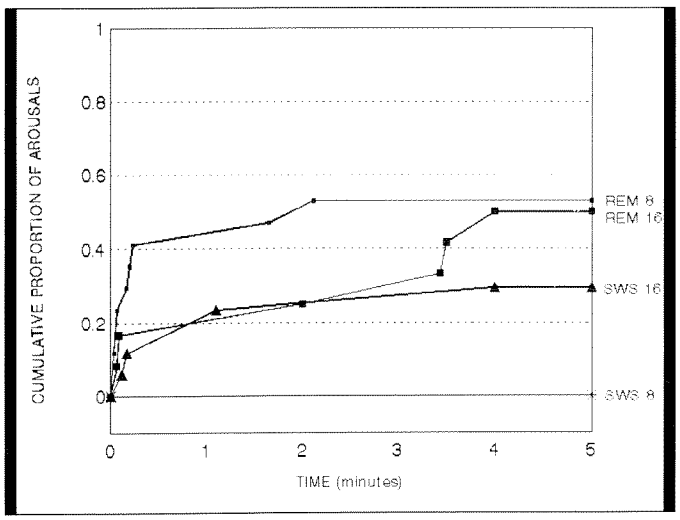

Figure 2.
Cumulative proportion of arousals as a function of warning signal type and duration. Data are averaged across all subjects and trials within the specified test condition (SWS 8 = slow-wave sleep with 8 μF light intensity; SWS 16 = slow-wave sleep with 16 μF light intensity; REM 8 = rapid-eye-movement sleep with 8 μF light intensity; REM 16 = rapid-eye-movement sleep with 16 μF light intensity).

Optical Testing

Procedure

The maximum candlepower in the main beam of the flashing signal lights was measured in a room that was completely dark. A photopically corrected photocell (SDC Corp. Model SD-444-31-12-173) was mounted on an ad-

Table 3.
Ratio of arousals to sleep trials at the 2.5 and 5 minute criterion as a function of light level, sleep stage (data for 13 subjects in Experiment 2).

		Stage of Sleep			
Control Setting	**Criterion**	**SWS**	**REM**	**Stage 2**	**Total**
8 μF	2.5 m	0/13	9/18	0/2	9/33
	5.0 m	0/13	9/18	0/2	9/33
16 μF	2.5 m	5/17	3/11	0/3	8/31
	5.0 m	6/17	5/11	2/3	13/31
Combined	2.5 m	5/30	12/29	0/5	17/64
	5.0 m	6/30	14/29	2/5	22/64

justable tripod at a distance from each light that was at least five times the largest dimension of the luminous opening of the light source under test. The photocell was connected to a Photodyne Digital Optical Power/Energy Meter Model 66XLA. The lights and the photocell were adjusted to the same height and oriented such that the cell was aimed directly at the main beam of the flashing light. The power to the light source under test was then turned on, the room lights were turned off, and measurements were made. The current energy generated by the light on the photocell was measured over a span of 10 flashes from the unit. This value was then divided by 10 to obtain the mean value per flash. Knowing the distance to the photocell, the area of the photocell, the current per lumen response rate of the photocell, and the average current generated by one flash, the instantaneous candlepower value of the flash can be calculated to yield the Instantaneous Candlepower. The effective candlepower to the human eye for a flash of very short duration is equivalent to five times the instantaneous value. The illumination created directly ahead of the light source can therefore be calculated for any desired distance from the light source.

Results

Table 4 summarizes the results of these measurements of the physical optical characteristics of the experimental light source and several representative visual smoke detectors. Two of these, the Gentex (GXS-20) and the Wheelock strobe light, exceed the ADA requirements; one, the 350-5 strobe, did not. (The following analysis will show that the test lights, being very close to the subjects, delivered more intense light to their eyes than would any presently available commercial light source.)

In the test position used in Experiment 2, the EEG strobe was lowered to 75 cm from the subject's head. This yielded a light level exceeding that which would have been achieved by any of the commercial smoke detector devices, when installed in a normal operating position. In this position, the light level at the subject's head was determined to be 19.9 Lux at the 16 μF setting and 7.6 Lux at the 8 μF setting. These values exceed those that would be obtained with normal installations, under even smoke-free conditions with the commercial devices.

DISCUSSION

This study developed and applied a procedure for testing visual alerting devices on sleeping humans. Unlike previous studies, the procedure provided a critically important control over the stage of sleep during testing. With this control, subjects did not wake consistently to the flashing light during the deepest stages of sleep. This result raises serious concerns about the safety of these devices during life-threatening situations.

In the normal operating position for smoke detector devices, on or near the ceiling at or beyond the foot of the

Table 4.
Summary of optical measurements for three commercially available smoke alarm systems and for the experimental light source used in behavioral testing.

Light Source	Wheelock (see LSC5263)	GXS-20	350-5	EEG Strobe (High setting) (16 μF)	EEG Strobe (2nd Highest setting) (8 μF)
Description of Optic	Xenon flash tube in parabolic reflector behind flat plastic lens	Xenon flash tube behind plastic hemispherical lens	Xenon flash tube behind plastic diffusing lens	Xenon flash tube in diffuse rectangular box with flat glass lens and protective metal mesh	Xenon flash tube in diffuse rectangular box with flat glass lens and protective metal mesh
Area of luminous opening (in m^2)	1.29×10^{-3}	8.067×10^{-4}	1.29×10^{-3}	4.034×10^{-3}	4.034×10^{-3}
Instantaneous Candlepower	31.38 cd	20.55 cd	0.386 cd	2.24 cd	0.860 cd
Effective Candlepower	156.9 cd	102.8 cd	1.93 cd	11.20 cd	4.30 cd
Illumination at 1m	156.9 Lux	102.8 Lux	1.9 Lux	11.2 Lux	4.3 Lux
Luminance	1.22×10^5 cd/m^2	1.27×10^5 cd/m^2	1496 cd/m^2	2776 cd/m^2	1066 cd/m^2

bed, the alerting device would be ≥ 3 m from the sleeper's face. At this distance, the commercially available smoke detector devices we measured would deliver a maximum of 17.3 Lux (Wheelock); 11.42 Lux (GXS-120); and 0.21 Lux (350-5) to the sleeper's face. In the testing position used in Experiment 2 (0.75 m from sleeper's face), the experimental light source used in our studies yielded 19.9 Lux (at the 16 μF setting) and 7.64 Lux (at the 8 μF setting). *The testing conditions therefore met or exceeded the levels provided by devices which are now widely available, and which meet current ADA specifications.*

In contrast to present results, measurements by UL suggest that the Gentex device provided higher light levels than the Wheelock device, whereas the measurements here show that the effective candle power of the Wheelock device was higher. The parabolic properties of the Wheelock device gave this strobe light the brightest rating because the photocell was so focused. Changes in measurement position (or in sleeping position), may interact with this strobe's directional properties and change the measured or perceived brightness. The directional relationship between the aperture of the strobe light and the position of the sleeper's head may affect effective light level in important ways, but it is unlikely that this factor is considered by consumers.

Deaf persons, who know of their dependence on visual alerting signals from home smoke detectors to wake them safely in the event of a fire, may demonstrate slightly *lower* waking thresholds due to the personal significance these signals have for them. However, it would be most imprudent to appeal to such "importance" factors to presume that the available visual alerting devices will wake such persons safely. In fact, since young university students with no health problems were used for this study, our results may be conservative. Several variables may *raise* the thresholds for waking beyond that seen here. These include sleep deprivation, fatigue, age, drugs, alcohol, exercise, chronic health problems, and medication, all of which might raise alerting thresholds even beyond those of the present study (5). The effectiveness of these devices must therefore be questioned, even under optimal circumstances.

In real-life situations, the presence of smoke would also obscure the visual signal. In view of this fact, the concern for safety generated by the results from this study is further enhanced. In practice, the effect of screening smoke should be factored into the intensity rating, since light obscuration will decrease effectiveness. UL reported that a 120 cd strobe would have to be increased to 195 cd (195/120 = 38 percent attenuation) to achieve, on average, an equivalent signal effect in the presence of smoke (5). Smoke obscuration increases with the height of the detector in a room, and smoke detectors are often located at or near the ceiling. Optimally, the detector would be located on the ceiling, to where the smoke is likely to rise, maximizing the sensitivity of the detector, while the strobe light should be located below this, to be closer to the sleeper to avoid the obscuring effects of smoke.

CONCLUSIONS

The purpose of this investigation was to evaluate the likelihood that a visual alerting device would be effective in waking a person from a "deep" stage of sleep. The results are clear: even under the favorable optical (smoke-free) conditions of the present study, the most intense of the devices presently offered for sale in Canada cannot be relied on to wake a sleeping person within 5 min. This is double the safe time recommended by the British fire safety code (1).

On the basis of these data, it is recommended that:

1. visual fire alerting devices should not be relied upon to alert sleeping persons;
2. other devices (vibrotactile/fans) should be tested under similar conditions to determine their suitability as fire alerting alternatives; and,
3. sleep stages should be monitored in subsequent evaluation of such alerting devices.

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