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THE EFFECTIVENESS OF DIFFERENT ALARMS IN WAKING SLEEPING CHILDREN

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Residential fire is a major cause of fire fatalities and smoke alarms are installed to promptly detect and warn people of fires so that action may be taken. Coronial reports of 114 fire fatalities in Australia noted that 81% of the fatal fires were at night and in those, 86% of victims were sleeping.[1] It is thus important that smoke alarms are as effective as possible in waking people up. A review of the research on who will wake up to smoke alarms under what circumstances[2] showed that there were many potentially vulnerable groups in the population, including children, the elderly, people under the influence of alcohol or drugs, and people who are sleep deprived. Most unimpaired adults will awaken quickly and reliably to a hallway alarm under normal circumstances.[3]

It has been found that only 6% of children (aged from 6 to 15) awoke reliably (i.e. to two out of two alarm presentations) to the Australian standard smoke alarm (a high pitch beeping signal) installed in the hallway and received at the pillow at 60 dBA.[3] When the volume of the signal was increased to 89dBA at the pillow, by installing the alarm above the child's bed, the percentage who reliably awoke increased to 50%.[4] However, the responsiveness of children is clearly age related, with the younger children being more at risk. Only 29% of those aged 6-10 years awoke reliably to 89 dBA.

The reasons why children seem to be particularly difficult to awaken may be related to their delayed prefrontal lobe development. This part of the brain develops mostly between ages 12 and 24 and is responsible for behaviours that include making judgements. If this includes both judgements while asleep as well as when awake then this may influence the arousability of younger children to a signal while sleeping. It is also known that the duration of deep sleep (stage 4) decreases with increasing age, so younger children spend more time in deep sleep than older children or adults. Perhaps more important, however, are the findings[5] that children may have higher electroencephalogram energy levels within sleep, making *all* stages of their sleep deeper and, it is hypothesised, harder to disturb than adults.

From a fire safety point of view the key question becomes - can we devise a signal that is more likely to awaken children than the high pitch beeping signal currently used in smoke alarms in Australia? It is not simply a matter of increasing the volume of the signal, as above 90 dBA there are concerns about the safety of the signals for hearing. In addition, one study found that some prepubertal children did not awaken to a signal being received during sleep at 123 dBA.[6] It is known that during sleep adults continue to monitor the environment and can make discriminations about what is relevant and meaningful to respond to.[7] If this is also the case for children, then their arousability to a signal may be enhanced if the signal is more significant to them. The literature would suggest that key factors in meeting this aim might include:

- ensuring the signal is not one that the child frequently hears while asleep, to prevent habituation,[7]
- increasing motivation to respond through prior education/priming ,[8]
- including relevant content in the signal eg. using a verbal message about the fire,[9]
- including words with an emotional content,[10]
- using a female voice, found to convey more urgency than a male voice,[11]
- including the child's name as part of the signal.[12]

It has also been suggested[13] that there may be some advantages to using a voice that is familiar to a child. Whether these advantages may include a comfort factor to the child on hearing a familiar voice in the midst of an emergency, or a hypothesised increased saliency of a signal that includes a familiar voice (and hence increased likelihood of waking up) is unknown. Recent research from our laboratory has suggested that the T-3 beeping sound, presented at a low pitch, may be more effective at arousing sleeping adults who are intoxicated with alcohol than the high pitch current Australian signal.[14]

In a fire situation there is a need to wake sleepers as quickly as possible and to also ensure that their ability to assess the situation and respond appropriately is maximised. Thus the time required to wake up to different signals is important, as well as a comparative assessment of clearheadedness. This term is used here to describe a self-report of sleep inertia, the grogginess that impairs effective decision-making and motor performance immediately upon awakening.[15]

The current paper presents three studies investigating the ability of four different 89 dBA alarm signals to awaken sleeping children aged 6 to 10 years. Study 1 consisted of the presentation of two voice signals. One voice signal was a prerecording of the mother's voice giving a message about a fire and repeatedly saying the child's name. The other message was a female actor's voice talking about the presence of a fire. The waking effectiveness of these two different voice alarms was compared to a different study (Study 2) which presented a Temporal Three (T-3) signal. The T-3 is now the signal of the International Standard for audible emergency evacuation signals (ISO 8201). The standard provides strict requirements for the temporal sequences of the signal but no guidelines for the signal frequency. A low pitch signal was used in Study 2. Study 3, as presented here, is a subset of the data presented in the Bruck and Bliss (2000) study,[4] where the 89 dBA signal was high frequency beeps, such as is produced by standard residential smoke alarms available in Australia. Only the data from children aged 6-10 years in the study is presented here. All signals are described in more detail below.

It was hypothesised that the two voice alarms would result in a higher rate of awakenings in the children compared to the two beeping alarms and that these awakenings would occur within a shorter time period for the voice alarms.

METHOD

Participants

All of the studies reported here involved children aged 6-10 years. They were recruited by word of mouth through friends of people at the university. In Study 1 and 2 normal hearing of the child was ascertained through report from the parent, while in Study 3 all children's hearing was tested by an audiology clinic and only children with hearing above the 90th percentile across all frequencies were included. In those potential participant children who did not meet this criterion (n = 3 out of the 31 aged 6-15 years that were tested for the Bruck and Bliss study[4]), all the deficiencies were in the high frequency range. As Study 1 and 2 involved low pitch signals it was felt that parental report of normal hearing would be sufficient as a screening measure. Demographic details (number, age and sex) of the children in each study are shown in Table 1.

Signals

All signals were received at the pillow at 89 dBA, plus or minus 3 dBA and lasted for 3 minutes. The standard volume of a commercially available smoke alarm at one meter is about 90 dBA. Background noise levels were not measured or controlled. The first night was always an adaptation night and alarms were not activated. A summary of the methodological details of each study is in Table 1.

Table 1. Summary of the key methodological features of Studies 1-3.

	Study 1	**Study 2**	**Study 3[4]**
Signals presented	mother's and actor's voice	low pitch T-3	Australian standard signal
dBA	89 ± 3 dBA	89 ± 3 dBA	89 ± 3 dBA
Signal frequency	315-2,500 Hz	500-2,500 Hz	Approx 4,000 Hz
Time of signal	1am	1am and 3am	1am and 3am
Participants (n)	N = 20 (10M, 10F)	N = 14 (8M, 6F)	N = 14 (10M, 4F)
Participants (age)	6-10 yrs	6-10 yrs	6-10 yrs
Signal delivery	Via speakers & laptop	Via speakers & laptop	Via smoke alarm on ceiling
Signal activation	2nd and 3rd nights	2nd and 3rd nights	2nd and 4th nights
Awake measurement	Actigraphy	Actigraphy	Actigraphy

Study 1: The mother's voice signal was pre-recorded in each home using a script and included the child's name at the rate of about once every six seconds. If two children being tested shared a bedroom, both names were included (order counterbalanced). The message said that there was a fire, they were to wake up now, and quickly go outside. The actor's voice signal was a female voice saying danger, there is a fire, they must wake up now and go and investigate. Both voice signals conveyed urgency, although the

actor's voice was typically more urgent. All messages lasted 30 seconds and were looped to make a 3-minute continuous recording. The female actor's voice was acoustically tested and found to be a complex sound within the frequency range from 315 Hz to 2500 Hz. The children were told that a signal could go off on any one or more of the three nights of the study.

Study 2: In this study the signal presented was the Temporal three (T-3) pattern. The frequency of the T-3 is not specified in the standard, but the signal used in this study was the same as that used in a previous study on the perceived urgency of the signal.[16] The T-3 signal was acoustically moderately complex, with dominant tones in the lower frequency ranges; 500 Hz, 1500Hz and 2500Hz. The children were told that a signal could go off on any one or more of three nights.

Study 3: This study was performed in 1999[4] and used a standard Australian smoke alarm bought in that year. This was a high frequency signal of approximately 4000 Hz. The children were told that an alarm would go off on two of the five nights of the study but they did not know which two nights. A subset of the total sample of children is included here, only those aged 6-10 years.

Note that for Study 2 and 3 each child got the same signal twice, but in Study 1 each of the two signals was only presented once to each child. All presentations were considered as independent events for the purposes of analyses (this assumption is discussed further in the results section). Thus the total number of presentations for the mother's voice was 20, actor's voice 20, low pitch T3 28 and standard signal 28.

Materials and procedure

All studies were conducted in the child's own home and the sound equipment set up in their bedroom. In Studies 1 and 2 each child participated for three nights. In Study 1 the actor's voice and mother's voice were presented at 1am, counterbalanced across all subjects, on either night 2 or night 3. In Study 2 the same T-3 signal was presented at either 1am or 3am on either night 2 or 3, with the order counterbalanced. In Study 3 the children were told the study was over five nights and the Australian standard signal was presented on nights 2 and 4 at either 1am or 3am, with the order counterbalanced across all subjects. All children had heard all signals prior to going to bed but they did not know on which nights the signals would occur. Study 3 was conducted several years before the other two studies and the test nights were made non-consecutive due to concerns about accumulating sleep deprivation. However, a questionnaire was repeatedly administered during that study[4] to test for sequential confounding effects of sleep deprivation and as none were noted this precaution was eliminated from subsequent studies.

All children were instructed that they must adhere to their usual 'school night' bedtimes for all nights while participating in the study (to minimise variable sleep patterns due to late nights or sleep deprivation[17]) and put on a wrist actigraph prior to going to sleep. This recorded their movement in time "bins". In Study 1 and 2 the time bins were of 15 seconds duration, while in Study 3, using older equipment, the time bins were of 16 seconds. For the comparative purposes of this paper the data from Study 3 was slightly rescaled so that all data fitted into the 15-second categories. Thus there may be inaccuracies of a few seconds in the sleep latency data for Study 3. The children were instructed to move their arm with the actigraph back and forward for 10-15 seconds as soon as they awoke to the alarm and then to leave their beds. This was to ensure that the actigraph recorded movement as soon as they awoke. In all cases a parent would awaken at the time of signal delivery. They were instructed to wait quietly until the child emerged from the bedroom (if awoken) and then the parent and child would go into the living room and together complete a short questionnaire, the "Upon Awakening Questionnaire" (UAQ).

The UAQ had 11 items that asked for information about sleep/wake behaviour before, during and after the alarm was activated. The children rated how clearheaded they felt at three different time points, with a rating of 1 indicating “extremely” clearheaded, 3 being “moderately” clearheaded and 5 “not at all”. The first and second ratings were retrospective evaluations, with the first being at the time the alarm was first heard and the second when the child got out of bed and left the room. The third ”right now” rating was completed when they had reached the living room and while completing the UAQ. The adapted Karolinska Sleepiness Scale was also completed on a ‘right now’ basis with a rating between extremely sleepy (1) and extremely alert (5). Those children who did not wake to the presented signals were not required to do anything during the night. In Studies 1 and 2 all children were paid $25 for their participation, while in Study 3 the only incentive to participate was the free hearing test. All studies were approved by the Victoria University Human Experimentation Ethics Committee.

RESULTS

Only data from children who reported that they were actually asleep at the time of signal presentation were included in subsequent data analysis. Of the 20 children in Study 1 (voice alarms), one child reported being awake at the time of the mother’s voice alarm activation and another child was awake at the time of the actor’s voice presentation, so those trials were not included. In Study 2 (T-3) and Study 3 (standard alarm) all children were asleep at both 1am and 3am when the alarms were activated. It was observed that most children in all the studies had a strong sense of anticipation of the alarms and motivation was high to “beat” the alarm by waking up.

Time of night

The first issue to be determined was whether there was a difference in awakenings between the 1am and 3am presentations. Table 2 presents a combination of this data from Studies 2 and 3 and shows that the number of children who awoke at 1am versus 3am did not differ greatly. Analysis of the frequency data with a Chi Square test revealed no significant effect of time of signal presentation (Pearson Chi Sq $X^2 = 0.59$, df = 1, $p > 0.10$). The ratings of clearheadedness at the three different time points, and the single rating of sleepiness, were all analysed individually to determine whether any differences existed between the 1am and 3am awakenings. A series of one-way ANOVAs found no significant differences (F values ranged from .204 to 1.006, with df = 1, 39 and all p levels were > .10). Thus in all subsequent analyses the 1am and 3am data were combined.

Table 2. Number of different responses at different time of night presentations of the alarm signal. Data from Studies 2 and 3 only.

	Slept	**Awoke**
1am	7	21
3am	6	22

Awakenings to alarms

Figure 1 displays the number of children who did or did not awaken to the various alarms. It can be seen that of the 19 valid presentations of the mother’s voice, all children awoke. One child did not awaken to the actor's voice (i.e. 94.4% awoke) and one child also did not awaken to one presentation of the low pitch T-3 (i.e. 96.4% awoke). By contrast, of the 28 presentations of the standard alarm, only 16 (i.e. 57.1%) awoke. Analysis of the frequency data with a Fisher Exact Test revealed a highly significant effect of the frequency of awakening to the different alarms (df = 3, p=.000). The data suggests this significant difference is due to the lower rate of awakenings to the standard alarm.

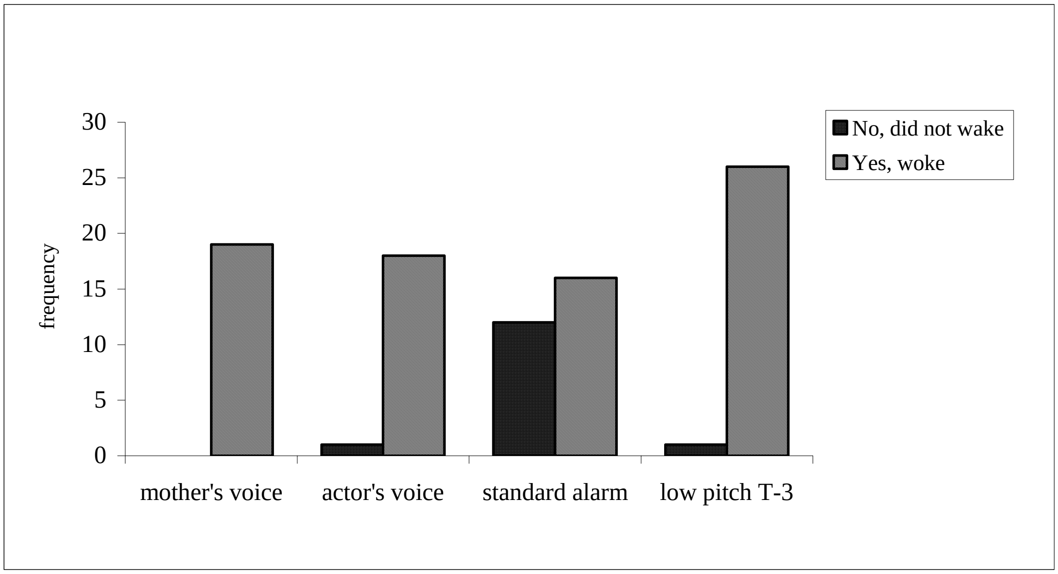

Figure 1. Number of children who did or did not awaken to the different alarm signals across all three studies.

In Study 2 (T-3) and Study 3 (standard alarm), each child received two presentations of the same signal, while in Study 1 (voice alarms) each child received each signal only once. However, as stated above, the analyses assume that all observations are independent. Thus the issue arises as to whether the high rate of sleeping through the standard alarm is possibly a confound of the different study designs. In Study 3 the fact that only 2 of the 14 children who slept through an alarm, slept through BOTH presentations of the alarm, suggests no such confound exists. In other words, there was no evidence of a subgroup of children in Study 3 who were consistently hard to awaken that could distort the findings.

In Study 3, of the 12 signal presentations that produced no awakening, in five cases the child stirred (as evidenced by movement recorded on the actigraph) but did not waken sufficiently to do the wrist movement for 15 seconds and leave their beds as instructed beforehand. Instead they returned to sleep. There were no cases of this happening with the other three alarm signals.

Time to awaken

Examination of the time required for the children to wake up (i.e. sleep latency) showed that the children took longer to arouse and begin shaking their arm (as required) with the standard alarm, compared to other alarms (see Figure 2). In order to determine whether significant differences were apparent in the sleep latency data the time categories were collapsed (enabling valid Chi Square calculations). The regrouped frequencies and percentages are shown in Table 3.

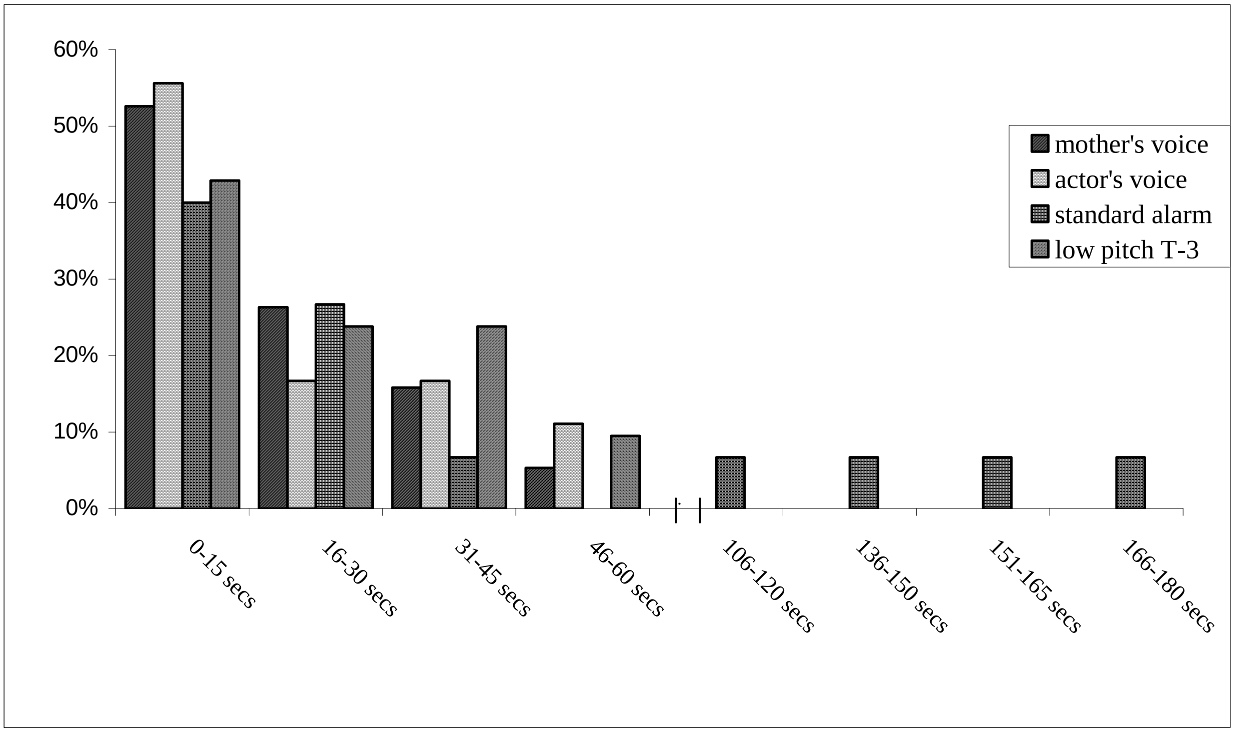

Figure 2. Percentage distribution of the time taken to awaken to different alarms.

Table 3. The number and percentage of children who woke within different time categories to different alarm signals.

	0 - 30 seconds	31 - 60 seconds	Over 60 seconds
mother's voice	15 (78.9%)	4 (21.0%)	0
actor's voice	12 (70.6%)	5 (29.4%)	0
standard alarm	10 (66.7%)	1 (6.7%)	4 (26.6%)
low pitch T-3	14 (66.7%)	7 (33.3)	0

For the voice alarms and T-3, all children gave the behavioural response within one minute, while for the standard alarm only 73.4% of the children responded as instructed within one minute. For the standard alarm 26.6% of the children took 106-180 seconds to wake up. In terms of response within 30 seconds, the actor's voice, mother's voice and low pitch T-3 were all similar, with the mother's voice performing slightly better. A Chi Square Test was performed on the frequencies as shown in Table 3 and it was found that the observed frequencies differed very significantly across the different alarm signals (Pearson Chi Square $X^2 = 18.022$, df = 6, p = .006). The data suggests that this significant difference is due to the slower awakening time with the standard alarm.

Clearheadedness upon awakening

Ratings of "clearheadedness" (on a 5 point scale) at three different time points after wakening (when the alarm first went off; when they got out of bed; when completing the questionnaire) showed no major differences between the four alarms. Table 4 reports the descriptive statistics of the clearheadedness ratings at the three different time points. The usual ratings were between 2 (quite a bit clearheaded) and 3 (moderately clearheaded) and mild improvement with time was typical. A multivariate analysis was conducted using all four signals and three time points. The overall F (Wilks'Lambda F = 1.5, df = 9, 175, p > .10) indicated no significant difference between alarms and no significant improvement with time.

Table 4. Mean ratings (and standard deviations) of ratings of clearheadedness at three different time points with different alarms (1 = extremely clearheaded and 5 = not at all).

	Alarm Signal	**Mean**	**S.D.**
how clear-headed when alarm went off	mother's voice	3.40	1.31
	actor's voice	2.88	1.16
	standard alarm	3.18	1.04
	low pitch T-3	2.20	1.35
how clear headed getting out of bed	mother's voice	2.75	1.25
	actor's voice	2.70	.98
	standard alarm	2.68	.94
	low pitch T-3	2.12	1.07
how clear headed right now	mother's voice	2.50	1.00
	actor's voice	2.23	1.30
	standard alarm	2.81	.98
	low pitch T-3	2.04	1.16

Table 5. Mean ratings (and standard deviations) of sleepiness of the different alarms (1= extremely sleepy and 5= extremely alert).

	Mean	**S.D.**
mother's voice	2.30	1.03
actor's voice	2.05	1.02
standard alarm	2.25	.85
low pitch T-3	1.92	.40

Sleepiness rating

Each child's sleepiness rating occurred an average of 7 minutes after the alarm had first been activated (with a wide variation of between 3 and 12 minutes). The mean ratings with different alarms are shown in Table 5 and indicate that all the ratings corresponded to an approximate rating of 2 (sleepy but no difficulty staying awake) and less than 3 (neither sleepy nor alert). A one-way ANOVA found no significant difference between sleepiness with different alarms ($F = 1.99$, $df = 3,75$, $p > .10$).

DISCUSSION

The hypothesis that the two voice alarms would awaken children more quickly and effectively compared to the two beeping alarms was not supported. In fact three of the signals were significantly more effective in awakening the children quickly than the fourth. The mother's voice awoke the children in 100% of the presentations, the actor's voice 94.4% and the low pitch T-3, 96.4%. In contrast, the high pitch standard alarm awoke the children in only 57% of the presentations.

This difference in waking effectiveness across the alarms was also reflected in the time required for the children to show they were awake by beginning to shake their arm. All children showed they were awake within one minute of the sounding of the two voice alarms and the low pitch T-3 signal. However, with presentations of the standard alarm only 73.4% awoke within one minute. Over a quarter of the children who awoke to the standard alarm took between 106 and 180 seconds to do so.

It was noted that in five cases with the standard alarm signal the child stirred but did not awaken, and that this did not happen with the other signals. It could be argued that the direct verbal instructions of the voice alarms may have played a part in fully awakening those children who had become aware, at a subconscious level during sleep, that there was a disturbance. However, this would not explain why the low pitch T-3 was also effective at waking the children.

The data show that responses to the T-3 and two voice alarms are all similar. The statistically significant findings arise from the poor performance of the standard alarm compared to the other alarm signals and are not due to differences between either the two voice alarms or between the voice alarms and the T-3. Further studies with more children are needed to determine if real differences between the three better performing alarms exist. These findings suggest that the effectiveness of an alarm signal is primarily the function of the *frequency of the signal*, wherein signals that are in the same pitch range as a voice (2500 Hz or less) are more effective than those of a higher pitch. This hypothesis is consistent with our findings in a different study,[14] of the differential decibel levels needed to awaken intoxicated young adults with different alarm signals. In order to confirm this conclusion, and rule out the possibility that there was another reason for the difference in arousal to the low pitch T-3 versus the high pitch standard signal, a similar study using a high pitch T-3 needs to be conducted. Such a study is currently underway within our research team.

It is possible that the rate of awakenings in these studies may be higher than in real life circumstances because the children knew that a signal would be going off on one or more of the nights that the equipment was installed in their bedrooms. Such "priming" has been shown to increase the likelihood of waking up, in one study increasing awakenings in adults from 25% to 90%.[8] To determine the influence of this factor with children, studies are needed where the equipment is installed for weeks or months and the signals activated infrequently. Nonetheless, the possible effect of priming would not alter the central findings of this paper, as the expectation effects would be consistent with the different alarms. The possible effectiveness of priming may, however, have implications for fire safety education with children.

The finding of no significant difference between the 1am and 3am signal presentations indicated that the two time groupings could be collapsed for the purposes of further analyses. Both time periods are in the middle third of a child's sleep period and, given what we know about arousal and how sleep changes across the night, [7,18] we could generalise these findings to the final third of the night. Arousals from sleep in the first third of a child's sleep are, however, less likely, given that this is the time of the deepest sleep. Further research on the possible difference between different alarms should be conducted in this earlier part of the night, to overcome a possible ceiling effect, whereby all or most children awaken.

We know that more deep sleep occurs in younger children than older people, that the density of the power spectrum during sleep decreases with advancing age,[5] and that the likelihood of arousal at lower volumes increases with age.[19] It was found in an earlier study on alarms[4] that the younger children (6-10 years) were more likely to sleep through alarm signals than older ones (11-15 years). Extrapolating from this data and what we know about sleep, we can assume that children aged below 6 years will generally be harder to arouse than the children tested in the studies reported here. In the course of a Study 1 re-enactment for the media a younger sibling (aged 5) of some participants also awoke to the voice alarms. Interestingly, he became distressed on hearing the actor's voice, hid under the bedcovers and needed comforting. This did not happen when he heard his mother's voice as the alarm signal. This anecdote may be worth following up to see if other young children also find an urgent, unfamiliar voice distressing just after waking up. In the absence of any findings to the contrary it should be assumed that most preschool children will need to be awoken and/or directed to safety by other members of the household in the event of a fire.

The subjective ratings of clearheadedness showed no differences across alarm signals or across different time points, while the sleepiness rating also did not differ with different alarms. These ratings are designed to be an approximate indicator of subjective sleep inertia, which has been shown[15] to impair decision-making in adults by up to 50%, especially in the first 3 minutes. While average ratings of feeling "quite a bit" to "moderately" clearheaded do not seem to be cause for concern about how children may react in a fire situation, studies testing sleep inertia objectively are required. Would a young child be able to make effective decisions on a specific computer task, for example, soon after being awoken from a deep sleep by an alarm? If such a computer task were a valid indicator of cognitive skills in an emergency situation, then the task would provide a more robust assessment as to whether different alarm signals have different implications for safe behaviours once awake.

Conclusions

The results of these three studies suggest that sleeping children aged 6-10 years are very likely to awaken to a voice alarm or low pitch T-3 presented at about 89 dBA during the middle third of the night, while only about half such children will awaken to a high pitch standard alarm under the same conditions. The fact that the low pitch T-3 was as effective as the voice alarms suggests that the critical factor is not the urgency of the message, its verbal content, or use of a voice in itself. The evidence suggests that responsiveness is primarily a function of the *lower frequency* of a signal. With further confirmation of this as a critical factor, specifications about signal frequency should be included in the standards for all residential alarms.

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