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SUMMARY

How arousal thresholds vary with different sounds is a critical issue for emergency awakenings, especially as sleepers are dying in fires despite having a working smoke alarm. Previous research shows that the current high pitched (3000+ Hz) smoke alarm signal is significantly less effective than an alternative signal, the 520 Hz square wave, in all populations tested. However, as the number of sounds tested has been small further research is needed. Here we measured auditory arousal thresholds (AATs) across signals with a range of characteristics to determine the most effective waking signal. Thirty nine young adults participated over three nights. In Part A, nine signals were presented in stage 4 sleep with ascending decibel levels. Signals were short beeps in the low to mid frequency range with different spectral complexities: square waves, pure tones, whoops and white noise. Part B manipulated temporal patterns, inserting silences of 0, 10 and 21 seconds after each 12 seconds of beeps. It was found that the low frequency (400 and 520 Hz) square waves yielded significantly lower AATs than the alternatives. A trend was found across the three temporal manipulations, with a 10 second intervening silence showing some advantage. These findings support earlier research indicating that the best sound for awakening from deep sleep is a low frequency square wave. It is argued that the signal with the lowest response threshold when awake may be the same as the most arousing signal when asleep, especially where the sleeper processes the signal as meaningful.

Keywords: auditory arousal, smoke alarms, wake thresholds, emergency signals

INTRODUCTION

Sleeping is a risk factor for death in a residential fire, even if a smoke alarm sounds. US fire fatality data shows that 37% of people who died in fires with working smoke alarms were sleeping when fatally injured (Ahrens, 2008). Thus the question arises, is there a better smoke alarm signal that has a lower (i.e. better) auditory arousal threshold (AAT) and thus will wake people more effectively?

The literature on arousal behaviour falls into two groups. The first group is dominated by researchers from the 1960s, 70s and 80s who were primarily interested in how arousal varied with characteristics such as sleep stages, time of night, age, sleep deprivation, individual differences, signal meaningfulness and chemical/alcohol intake (Bonnett, 1982; Bruck, 2001). The second group involves researchers interested in human behaviour in fire and emergency signals. Research in this area began in a small way in the 1980s and continues to the present with different auditory signals (Bruck and Ball, 2007; Bruck and Thomas, 2008a) and also tactile and visual stimuli (Bruck *et al.*, 2007; Bruck and Thomas, 2007) being compared in terms of their ability to wake up people quickly, as would be relevant in a fire.

Our team began work in this second area hypothesising that the significance of the signal would be critical in determining how easily people awoke. This was based on research showing that sleeping people would respond much more easily to their own names than other names (Oswald *et al.,* 1960) and also drew on Gibsonian theory (Gibson, 1979) that suggested people perceive stimuli more readily if the stimulus itself conveys the meaning, without the requirement that the meaning has been learnt.

The Gibsonian principle had been applied in a study of alarms used in Intensive Care Units (Stanton and Edworthy, 1998), where alarms that used traditional auditory warnings were replaced with sounds considered to be "representative" of the particular medical information they were trying to convey. It was found that staff who had not been trained in the traditional warnings had significantly better recognition and subsequent performance with the new representative sounds than the old signals. This principle was applied to test both naturalistic fire sounds and a direct voice message in different sleeping populations and we found, surprisingly, that the fire sounds were quite ineffective as alarms and the voice was either equally (Ball and Bruck, 2004; Bruck *et al.,* 2004), or less effective (Bruck *et al.,* 2006), than a low pitch beeping sound.

It was speculated that during sleep individuals may be selectively responsive to sounds in the same frequency range as speech, and this is consistent with the findings of an early study on neonates (Weir, 1976). When people are awake, sounds at a high pitch are better at attracting attention (Hellier *et al.,* 2002). However, when the research question is framed in terms of *audibility thresholds* when awake the literature suggests that mixed sounds with energy peaks in the low and mid frequency ranges (e.g. 500, 1000, 1600 Hz) are most easily heard by both young and older adult samples with normal hearing (Berkowitz and Casali, 1990; Hunt, 1970) and people who are hard of hearing (Bruck and Thomas, 2007).

Table 1 presents a summary of the research that has compared a variety of signals and shows the percentages that awoke at specified volumes. All studies, except the one involving children, controlled for sleep stage and used repeated measures designs.

Insert Table 1 about here……………….

Table 1 shows that comparisons of the waking effectiveness of the different signals presented have yielded quite consistent findings across the groups tested (i.e. across different age groups, under conditions of alcohol impairment and with adults who are hard of hearing). In all studies where the 520 Hz square wave was tested a significant difference ($p<.05$) was found between the 3000+ Hz pure tone (the current smoke alarm signal) and the 520Hz square wave, with the latter being more effective at waking sleepers. A square wave consists of a fundamental (f) and an infinitude of *odd only* harmonics of overall decreasing volume level. Thus the frequency peaks are at f, 3f, 5f, 7f, 9f etc. An example of a square wave spectral analysis is shown in Figure 1.

Insert Figure 1 about here……..

The differences in the waking effectiveness of signals are substantial. For example, in the case of children, the ratio of awakenings to the 520 Hz square wave versus 3100 Hz pure tone signals was 12:1 (at 89 dBA) and for the hard of hearing adults 7:1 (at 75 dBA). While the earlier studies with children and self-reported deep sleeping adults found that the voice signal was about as effective as the 520 Hz square wave this finding was not upheld when older adults were tested, with the voice doing quite poorly in terms of AATs.

The research presented in Table 1 highlights pitch as a potentially important characteristic in the design of alarm signals that may be needed to alert people who are asleep. The results provide no support for the study (Hellier *et al.,* 2002) which identified that signals of a higher pitch are more successful in gaining the attention of people who are awake. While not directly testing their additional finding that a beeping signal is more alerting with increasing speed of repetition (Hellier *et al.,* 2002), no advantage for a rapidly repeating signal was found. Instead, Table 1 shows that a rapidly repeating 3000Hz signal (presented in the 2004 studies) was less effective than the other beeping sound (520 Hz square wave) which was presented in the slower Temporal Three (T-3) pattern.

With the exception of the voice signal, there is good consistency in responsiveness to different signals across sleeping groups and conditions. This is encouraging because in this paper we recruited young adults to compare different signals and hypothesised that the results could be generalised to other groups who are “at risk” for sleeping through an alarm. It is argued that the young adults are a ”model” population, and that the signal with the lowest AAT in these young adults will also be the signal most likely to have the lowest thresholds in other population groups.

One factor that is evident from Table 1 is that not many different signals have been compared and that more comparisons, with more manipulations of different pitches and patterns, is needed in order to more precisely find which signal may be the most effective in waking people. In the following investigations a number of signals were compared, with the rationale for the signals chosen being that they were sounds within low and mid range frequencies (within the human speech range) and of different levels of spectral complexity.

In two studies, one involving hard of hearing participants (Bruck & Thomas, 2007) and the other 0.05 Blood Alcohol Content (BAC) young adults (Bruck *et al.,* 2007), analyses were made of the timing of awakenings in relation to signal onset and offset. Such analyses were possible as periods of 30 seconds of silence were inserted between each volume level of the signals tested. It was found that most participants who woke up did so within the first 10 seconds of signal onset, typically with 65-80% of awakenings falling in this time period. Thus it is feasible that AATs may be reduced by using a signal with a pattern that includes silences (of unknown duration).

The aim of Part A was to determine the signal with the lowest AAT from a variety of T-3 signals with complex low to mid range frequency components. Building on previous findings, it was hypothesised that the 520 Hz square wave signal would result in the lowest AAT. Part B sought to determine whether AATs are significantly improved by inserting different periods of silence (i.e. 10 or 21 seconds) into an ongoing signal. It was hypothesised that such silences would reduce AATs in comparison to a signal with no periods of silence.

In the following study the design involved all signals being delivered in only one stage of sleep as the focus was on signal *differences.* The deepest stage of sleep, stage 4, was chosen primarily as it was more likely to avoid a floor effect, whereby participants might wake easily to all signals. In addition stage 4 sleep presents the worst case scenario for waking up to an emergency signal, which is of relevance given that most fire fatalities occur early in the sleeping period (Thomas and Brennan, 2002), when people are in their deepest sleep.

METHOD

Participants:

Thirty nine people (18 males, 21 females) aged 18 to 27 years [Mean (SD) = 21.6(2.6)] participated in both Parts A and B. The inclusion criteria stated that they self-report usually having no difficulty getting to sleep; no sleep disorder; and no medication that affects their sleep. All participants were required to undertake a free hearing screening test and have auditory thresholds of 20 dBA or less at 500, 1000, 2000 and 4000 Hz. Recruitment was conducted on university campuses, targeting psychology students. Participants were paid $80 per night, with a completion bonus of $180 on completing three nights of the study.

Apparatus:

Hearing was screened with an Endomed SA 210/2 #13355. Polysomnographic sleep recordings were conducted with the Compumedics Siesta or Series E data acquisition system. A laptop computer was used to monitor sleep patterns and deliver the sound signals, via a speaker placed at head level one meter from the pillow. A behavioural response button (with a small LED light) was placed at the bedside. All sounds were delivered using a computer program that presented each sound for a set period at the nominated starting intensity and increased the volume by set increments. The program automatically stored the behavioural response times and the signal levels presented. A hand held Lutron SI-4001 sound meter was used to calibrate sound levels. Each sound was originally created on a computer and then for each sound a series of sound files at different volumes were created in a TV studio and played via the laptop. Details on sound measurement, calibration and delivery are as used in previous research and detailed elsewhere (Bruck *et al.,* 2006). All sounds were played in the Temporal-Three (T-3) pattern which is defined in ISO 8201-1987 as the emergency evacuation temporal pattern. One cycle of the T-3 consists of three ON signals of 0.5 s each, with a 0.5 s OFF period of silence between each signal. Each series of three signals is separated by a 1.5 s silence. The sounds used in Part A were as shown in Table 2.

Insert Table 2 about here….

The sound used in Part B was chosen from the first eight signals presented in Part A (as listed in Table 2), with the signal which yielded the lowest AAT being used. The temporal pattern manipulations of Part B are shown in Table 3.

Insert Table 3 about here…..

Procedure:

Each participant had their sleep monitored on three separate nights, typically in their own homes although about a quarter of the participants took up the option of being tested in the campus sleep laboratory. Four different signals were presented each night. Tests were at least one week apart to allow for recovery from any sleep deprivation. The participant was required to sleep on their own with the bedroom door closed.

All participants were told they needed to have an average or above average sleep (for them) the night before testing, that no alcohol could be consumed on the testing day and that it was important that all days of testing were as similar as possible. A questionnaire was completed each testing night to check these requirements and in all cases they were met. The sleep technician (ST) arrived at the participant's home about one hour prior to their usual bedtime.

After preparation for sleep monitoring the participant was instructed that when they awoke to a signal they should press the button by their bedside three times. They knew they would be awoken four times per night but had not heard the sounds beforehand. After each signal they should try to return to sleep immediately. The ST was in the hallway outside the bedroom monitoring their sleep patterns on a laptop computer. When the participant entered stage 4 sleep the ST waited 90 seconds before delivering the sound. If the participant moved to a lighter sleep (e.g. stage 3 or 2) then the ST waited till they again reached stage 4 sleep and maintained it for 90 seconds. The automatic sound delivery program was then commenced, set to play the required auditory signal. The first four signals listed in Table 2 were presented on night one and the next four signals in Table 2 were presented on night two. On the third night the final signal listed in Table 2 plus the signals listed in Table 3 were presented. The order of the presentation of the signals within each night was counterbalanced across participants. Counterbalancing of all signals across all nights was not possible as the results from the first block of four informed the characteristics of the next five signals tested. Arousal thresholds are unaffected by a first night effect (Sforza *et al.,* 2008).

Sounds were delivered at ascending volumes. This meant that each signal was presented at each volume level for a set time period (30 seconds in Part A and 66 seconds in Part B), beginning at a low pillow volume level (35 dBA) and increasing in volume (by 5 dBA in Part A and 10 dBA in Part B) until the participant pressed the button. The loudest signal was 95 dBA and this continued for a total of three and a half minutes, or until awakening occurred, whichever occurred first.

This research was approved by the Victoria University Human Experimentation Ethics Committee.

Data analyses:

For all analyses the dependent variable was the auditory arousal threshold (AAT) which was the decibel level for each signal at which the participant awoke (defined using EEG criteria). For each awakening the polysomnographic data were subsequently examined by an independent assessor (author MB) to both confirm that the participant was in stage 4 sleep at the time of signal commencement and calculate the exact waking time. (Some nights were repeated with some participants to ensure consistent stage 4 signal delivery.) Where there was any doubt or ambiguity these EEG records were independently re-assessed (author DB). The time at which the EEG waves altered from the patterns characteristic of sleep (in its various forms) to a wake pattern (very low amplitude and high frequency waves as defined in Rechtschaffen and Kales, 1968) was recorded. The wake pattern needed to be sustained for at least 15 seconds of the EEG trace to be considered a confirmed awakening (although wake time was recorded from the beginning of this sustained burst). This was usually (but not always) accompanied by an increase in muscle tone. Where there was ambiguity, the time at which changes occurred in both tracings was selected. In all cases where this wake criterion was met the participant remained awake and responded behaviourally (pressing a bedside button three times) and this was the signal for the sleep technician to terminate signal delivery. This usually occurred within several seconds of the appearance of the wake pattern.

Where a participant did not wake up the AAT level was assigned as 100 dBA to allow for statistical analyses to include that result. Statistics were conducted on a between groups basis (rather than repeated measures) to ensure the maximum number of valid data points could be included in the analyses. Valid AATs were not available for all signals from all participants, typically due to factors such as a participant not returning to stage 4 sleep or technical difficulties. Specifically, the number of participants from whom valid data was obtained for the final signal listed in Table 2 (and 4) was reduced by technical difficulties arising from this signal being presented on the same night as Part B signals, which had a different ascending decibel increment. The SPPS 14 package was used and alpha was set at 0.05.

RESULTS

The AAT data for Part A is presented in Table 4. A one way analysis of variance was conducted across the nine signals and a highly significant difference was found, $F(8, 217) = 9.6$, $p = .000$. It can be seen that in only one case did a person not wake up to the highest intensity signal, and this was for white noise.

Differences between selected signals were further explored using post hoc tests (Least Significant Difference Test). As it was hypothesised that the 520 Hz square wave signal would have the lowest mean AAT, differences between this signal and all others were analysed and the significance levels obtained are shown in the final column of Table 4. These indicate that the 520 Hz signal AAT was significantly different to all other signals ($p<.05$) except the 400 Hz square wave signal. Similar statistical outcomes would have been obtained if the 400 Hz square wave had been used as the comparison signal. The large standards deviations and ranges shown in Table 4 indicate the wide individual variability in arousal thresholds recorded in the study.

Insert Table 4 about here….

Part B considered whether the ON/OFF pattern of the 520 Hz square wave T-3 signal affected waking effectiveness and compared three signals with different patterns (see Table 3 for details). Table 5 presents the descriptive data. A one way analysis of variance found no significant difference in AATs between the three signals, $F(2, 58) = 2.9$, $p = .063$. However, there was a trend for the two signals with intervening silences (of 10 seconds or 21 seconds) to have slightly lower AATs than the continuous signal.

Insert Table 5 about here…..

DISCUSSION

The hypothesis for Part A, that the 520 Hz square wave signal would lead to the lowest AAT, was supported. This signal awoke participants at a significantly lower volume than the white noise, whoops, pure tone combinations, square wave combination signals and square wave signals with fundamentals at 800 Hz or higher. The 520 Hz and 400 Hz square waves were not significantly different from each other, with the mean AATs showing less than 1 decibel difference. This result is consistent with the previous research in the area, as summarised in Table 1, in several ways. It shows that the 520 Hz square wave has a very similar AAT to the 400 Hz square wave, although in all three studies where comparisons have now been made the mean values show the 520 Hz wave does marginally better. Further, the present result is also consistent with the previous data showing that pure tones, even at equivalent frequencies, are significantly less effective than complex tones. Both the white noise and whoops performed poorly.

The reason for the greater waking effectiveness of low frequency square waves may relate to the concept of critical band widths (Zwicker *et al.,* 1957). The various frequency peaks of low frequency square waves (as shown in Figure 1) lie more than a critical band width apart and this creates a loudness summation, giving the impression that the sound is louder (although this is not reflected in sound meter levels). This arises because the different frequencies activate different parts of the basilar membrane. This concept would help explain why voice alarms, which also include a range of frequencies (but without clear peaks that are more than critical band width apart), are not as effective for adult populations (Bruck and Thomas, 2008b).

Various researchers have considered the nature of the most effective alarms and/or ringer tones for alerting people who are awake. Patterson (1990) notes,

> Contrary to the general conception of pitch perception, we do not hear a separate pitch for each peak in the spectrum of a sound. Rather, the auditory system takes the information from temporally related components and maps them back onto one perception, namely a pitch corresponding to the fundamental of the harmonic series implied by the related components. (pg. 488)

Berkowitz and Casali (1990) tested the audibility of various ringer tones in both 20-30 year olds and 70-95 year olds and found that the "electronic bell" had the best (lowest) audibility thresholds for both age groups. They attributed this to the bell's prominent energy peaks between 1000 and 1600 Hz, with less effective alternatives having more high frequency content. Their findings were consistent with an earlier report by Hunt (1970) who used the theory of critical band masking to predict the most effective telephone ringer tone. Hunt concluded that at least two spectral components between 500 and 4500 Hz were desirable to aid detection of a ringer above background noises. Moreover, Hunt cited an earlier research report by Archbold and colleagues (1967) that concluded that at least one of these components should be less than 1000 Hz. These recommendations are all consistent with the idea that sounds with multiple frequency peaks that activate different parts of the basilar membrane have lower audibility thresholds.

Moreover, the efficacy of the square wave with a fundamental of around 520 Hz is consistent with a body of data suggesting that frequencies in this vicinity may have optimal audibility when awake. The hearing thresholds reported by Cruickshanks *et al.* (1998) in their population-based study of 3,753 people aged 48-92 years found that the average thresholds for the 500 Hz sound were lower than for 250 Hz, 1000 Hz, 2000 Hz, 3000 Hz and higher frequencies. Similarly, audiological screening tests of participants (when awake) with mild to moderate hearing loss involving a range of pure signals found the lowest thresholds for sounds with dominant frequencies around 500 Hz. Further awake testing of these participants using the first eight alternatives listed in Table 2 found the 520 Hz square wave had the lowest mean audible response threshold (Bruck and Thomas, 2007).

Given the above research, the waking effectiveness of the low frequency square wave is consistent with the idea that the most detectable signal when awake may also be the most alerting when asleep. Theoretically, *sensory processing* (or sensation) occurs when sound waves stimulate structures within the ear. When arousal occurs sensory processing has successfully moved onto *perceptual processing* whereby the signal is <u>interpreted</u> with reference to the external stimulus (Colman, 2006). Whether or not sensory and perceptual processing lead to waking in a sleeping person exposed to a signal may be a function of individual factors, an interaction between signal and environmental factors and motivation (Bruck and Ball, 2007). Various early studies support the possibility of introducing a motivational bias (or priming) while people are asleep (see review by Bonnet, 1982), with perhaps the most dramatic findings being that the percentage awoken from the deepest stage of sleep increased from 8% to 100% when subjects were motivated to respond to a certain signal and that discrimination during sleep can occur between a telephone ring and a door bell (Zung and Wilson, 1961, Wilson and Zung, 1966).

Consistent with this, research at a neurophysiological level suggests that auditory messages sent by cells in the thalamus to cortical neurons, while being reduced during sleep in terms of their firing rate and frequency range, nevertheless retain sufficient informative content to allow content analysis of some complexity (Edeline *et al.,* 2000). During slow wave sleep sensory blocking reaches a maximum, with thalamocortical cells being deeply hyperpolarized, and consequently sensory information has to be more *intense* or more *relevant* (perceptually) to overcome the sensory 'gate' and be evaluated by the sleeping cortex (Coenen, 1995; Coenen and Drinkenburg, 2002). Waking causes changes in the discharge threshold of thalamocortical neurons and allows a more ready transfer of information from the peripheral sense organs to both the sensory and higher order processing areas of the cortex.

The studies presented in this paper have only considered variability in responsiveness at the sensory processing level because all the participants have been primed to wake up to signals while they are asleep. There is no expected variability in perceptual processing because the subjects have all been instructed that they must give a certain behavioural response when they hear a certain signal (i.e. primed to perceive *all* of the presented signals as significant). Thus the research has effectively been testing which signal is most likely to initiate successful sensory processing and the variability is a function of differences in passing the sensory 'gate', with *intensity* being the parameter of most relevance. It is argued that the results indicate that the signal properties that affect human audible sensory processing are identical under awake and asleep conditions, but differ in terms of threshold.

However, in an unprimed home situation it is possible that only some sounds would be considered significant, with the perceptual processing leading to arousal. Whether a smoke alarm sounding the T-3 signal would be interpreted as significant may depend on a wide range of factors, such as the number of other beeping noises in the environment (e.g. car alarms, trucks reversing), previous experience with smoke alarms or fire situations and/or regular education about alarm signals. We know that sleepers can habituate to certain noises, resulting in reduced responsiveness with repeated exposure (Firth, 1973; Oswald *et al.,* 1960). For the most effective emergency signal it is important that (i) its spectral characteristics optimise low response thresholds when awake and asleep, (ii) people are educated about its nature, and (iii) it is easily differentiated from other signals in the environment. The first point will facilitate sensory processing and the second and third points will enhance meaningful perceptual processing (and thus waking up). Signal detection theory would argue that these three points would increase the *sensitivity* to detecting the signal and the level of a person's *bias* (or criteria) in terms of the consequences of a false alarm (waking when there was no need) or a missed response (not waking in an emergency).

In Part B of the study it was hypothesised that AATs would be improved by inserting periods of silence (10 or 21 seconds) into an ongoing T-3 signal. This hypothesis was not supported by any significant differences being found, although there was a trend (p=.06) for the inserted silences (especially 10 seconds) to improve the waking effectiveness of the signal. Power analyses suggest that a sample of 20 is only sufficient to obtain a significant difference if a large effect size (f >.4) exists. Thus it may be a Type 2 error to conclude from this data that intervening silences have no effect on AAT, however, it seems that the effect of intervening silences, if any, is not large. Further research with a larger sample size is needed to make a firmer conclusion.

Caution must be exercised in extrapolating aspects of this study to field settings. There are many reasons why the decibel levels of the AATs found in this research cannot be generalised. The *population*s used in this study, and all the studies listed in Table 1, are highly selected with people with certain characteristics excluded (e.g. medication/alcohol use, physical or mental disabilities, sleep problems or deprivation). In addition, the *methodology* of these studies was highly controlled, with awakenings from specified sleep stages and participants primed to expect signals during their sleep. An example of how the methodology influences AATs can be seen by the higher mean AAT for ongoing 520 Hz signals in Part B (52.4 dBA) compared to Part A (45.5 dBA). This difference is most likely to be a function of the different methodologies employed - 10 dBA increments for level of each signal in Part B compared to 5 dBA increments in Part A - with the different increment levels affecting the threshold averages yielded.

Conclusions:

The low frequency (400 and 520 Hz) square waves yielded significantly lower auditory arousal thresholds (AATs) than white noise, pure tones, whoops and higher frequency square waves. There was no significant advantage in presenting ongoing beeps with 10 or 21 seconds of intervening silence, although a trend for lower AATs with 10 seconds of intervening silence every 12 seconds was found. These findings support our earlier research showing that the best sound for awakening from deep sleep is a low frequency (e.g. 520 Hz) square wave. It is argued that the signal properties that affect human audible sensory processing are identical under awake and asleep conditions, but differ in terms of threshold. Further, waking will be facilitated by perceptual processing that a signal is meaningful and should be responded to. The results have implications for smoke alarm signals and other alarms sounding during the sleep period (e.g. to treat bedwetting).

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Table 1; Percentage sleeping through different sounds, as found in auditory arousal research comparing possible smoke alarm signals. (Unless otherwise specified all non-voice signals were in the Temporal 3 pattern.)

Participants	*decibel level (duration in sec)*	*N*	*Sleep stage*	***3100+ Hz pure tone***	***Voice***	***450 or 500 Hz pure tone***	***400 Hz square wave***	***520 Hz square wave***	*Reference*
young adults (18-26 yrs)	75 (30 s)	24	4	31%				0%	Bruck and Thomas 2008a
older adults (65-83 yrs)	75 (30 s)	42	3	18%	14%	15.5%		4.5%	Bruck & Thomas 2008b
young adults, 0.05 Blood Alcohol Content	75 (30 s)	32	4	38.5%		14%	7%	0%	Bruck et al. 2007
hard of hearing adults	75 (30 s)	38	3/4	56%			13.5%	8%	Bruck & Thomas 2007
hard of hearing adults	<75 (120 s)	45	2, REM & 3/4	43%		8%			Du Bois et al. 2005
adults	<75 (120 s)	34	2, REM & 3/4	0%		0%			Du Bois et al. 2005
deep sleeping young adults (18-26 yrs)	75 (30 s)	14	4	43%[a]	14%			7%	Ball & Bruck 2004
young adults, 0.08 Blood Alcohol Content	75 (30 s)	14	4	64%[a]	43%			50%	Ball & Bruck 2004
children (6-10 yrs)	89 (180s)	19-28	not controlled	43%[a]	3.5%			3.5%	Bruck et al. 2004

[a] The signal was not in the Temporal Three pattern. It was a succession of rapidly repeated beeps, as in Australian smoke alarms at the time.

Table 2: Details of the signals presented in Part A.

Signal name	**Signal spectral details**
400 Hz square wave	Each 0.5 sec sound had a fundamental at 400 Hz, with peaks of decreasing intensity at 1200 Hz, 2000 Hz, 2800 Hz, 3600 Hz etc
520 Hz square wave	Each 0.5 sec sound had a fundamental at 520 Hz, with peaks of decreasing intensity at 1560 Hz, 2600 Hz, 3640 Hz, 4680 Hz etc (see Figure 1)
800 Hz square wave	Each 0.5 sec sound had a fundamental at 800 Hz, with peaks of decreasing intensity at 2400 Hz, 4000 Hz, 5600 Hz, 7200 Hz etc
1600 Hz square wave	Each 0.5 sec sound had a fundamental at 1600 Hz, with peaks of decreasing intensity at 4800 Hz, 8000 Hz, 11200 Hz etc
White noise	Each 0.5 sec sound had a flat power spectral density across all audible frequencies
400 to 1600 whoop	Each 0.5 sec sound had a single, flat frequency "peak" that continued across the frequency band between 400 and 1600 Hz
400 to 800 whoop	Each 0.5 sec sound had a single, flat frequency "peak" that continued across the frequency band between 400 and 800 Hz
3 pure tones at 400, 800 and 1600 Hz	Each 0.5 sec sound in each pattern of three (T-3) consisted of a different pure tone, presented consecutively from low to high frequencies.
3 square waves at 520, 800 and 1200 Hz	Each 0.5 sec sound in each pattern of three (T-3) consisted of a different square wave signal, presented consecutively from low to high frequencies.

Table 3: Signals presented in Part B.

Signal name	Signal details
ON continuously	520 Hz square wave T-3 ON continuously for 66 seconds at each volume
ON 12/OFF 10	520 Hz square wave T-3 ON for 12 seconds, then OFF for 10 seconds, with the pattern repeated for 66 seconds at each volume
ON 12/0FF 21	520 Hz square wave T-3 ON for 12 seconds, then OFF for 21 seconds, with the pattern repeated for 66 seconds at each volume

Table 4: Statistics of auditory arousal thresholds (AATs, in dBA) for the signals presented in Part A. Final column shows post hoc test results comparing the 520 Hz square wave AAT with AATs of other signals.

	N	*Mean AAT*	*SD*	*Minimum*	*Maximum*	*post hoc p level*
400 Hz square wave	29	46.2	7.0	35	65	.831
520 Hz square wave	28	45.5	6.9	35	65	comparison signal
800 Hz square wave	27	51.8	10.1	35	70	.049
1600 Hz square wave	28	53.2	9.7	40	75	.016
White noise	24	59.6	18.1	35	100	.000
400 to 1600Hz whoop	27	61.3	16.7	35	95	.000
400 to 800 Hz whoop	27	66.3	12.9	40	95	.000
3 pure tones at 400, 800, 1600 Hz	22	60.5	9.3	40	85	.000
3 square waves at 520, 800, 1200 Hz	14	54.6	10.8	35	70	.020

Table 5: Descriptive statistics of auditory arousal thresholds (AATs, in dBA) for the signals presented in Part B.

	N	*Mean AAT*	*SD*	*Minimum*	*Maximum*
ON continuously	19	52.4	7.3	45	65
ON 12/OFF 10	22	47.3	6.1	35	65
ON 12/OFF 21	20	49.5	6.9	45	65

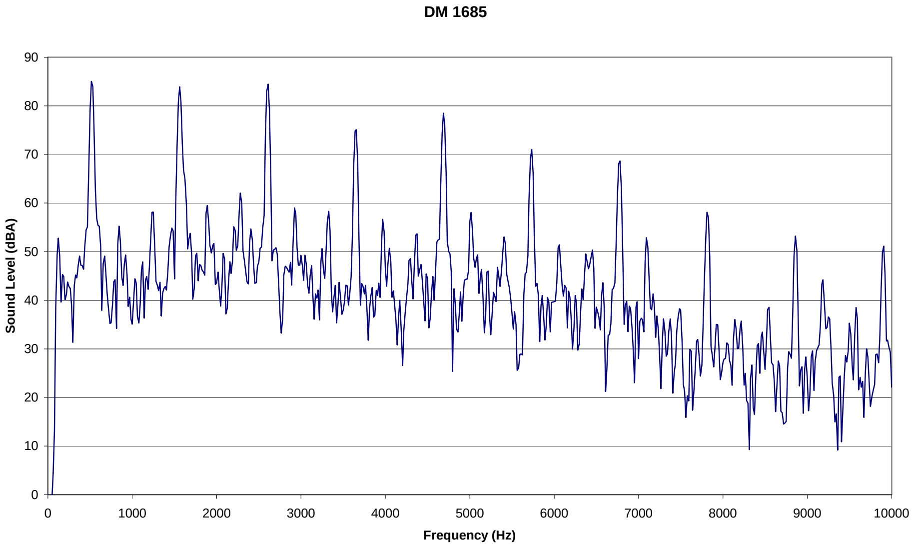

Figure 1: Spectral analysis of the 85 dBA 520 Hz square wave in the testing bedroom