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THE EFFECTIVENESS OF THE DOMESTIC SMOKE ALARM SIGNAL

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ABSTRACT

This research set out to determine if the signal from an inexpensive domestic smoke alarm is effective at providing early warning to a fire.

An experiment was devised to investigate the effectiveness of the inexpensive domestic smoke alarm signal at alerting occupants to a fire event. The experiment involved constructing an alerting device which could sound an alarm, identical to that of a domestic smoke alarm, at predetermined times between 6pm and 6am. Volunteers from the risk groups of students, Maori and elderly participated for two weeks in the experiment by allowing an alerting device to be installed in their home and responding to three alarm calls. Data from the experiment was used to examine response times to the alarm signal and identify who is particularly at risk to harm from fire. Analysis of the data from the experiment aimed to conclude if inexpensive smoke alarms are effective at alerting occupants to a fire event.

The inexpensive domestic smoke alarm signal was found to be 85% reliable at alerting occupants to a fire event, with children aged under ten years and adults whose sleep was influenced by the effects of alcohol identified as not being reliably woken by the alarm.

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CHAPTER 1: INTRODUCTION

1.1 Why Study Domestic Smoke Alarms?

For as little as $NZ8, a stand-alone smoke alarm can be purchased from a supermarket, department or hardware store. Provided with the alarm are a set of instructions as to how to install and maintain the mechanism. Reputable brands, registered to the standards acknowledged by the prefixes ANSI (American National Standards Institute), AS (Australian Standard), BS (British Standard), ULC (Underwriters Laboratories Canada) and ULI (Underwriters Laboratories Inc) assure, if installed and maintained correctly, the reliability of the alarm as an early detector of fire. Less reliable are the human behavioural aspects associated with the installation, maintenance and response to the alarm signal.

The following research sets out to determine if a signal from an inexpensive domestic smoke alarm is effective at providing early warning to a fire.

1.2 Research Impetus

The impetus for this research arises from publicity associated with the installation of inexpensive, domestic smoke alarms. A project funded by the Christchurch City Council, Canterbury, New Zealand offers an arrangement where for $NZ8, (subsidised if required) a stand-alone ionisation smoke alarm can be purchased and installed in a private home; Housing New Zealand plan to fit all their rental properties with smoke alarms, free of charge to the tenants; the New Zealand Fire Service are promoting the benefits of purchasing and installing inexpensive domestic smoke alarms. Concerns have been raised as to the reliability and ability of these inexpensive smoke alarms to produce signals loud enough to be effective at alerting occupants to a fire event.

Advice regarding installation of smoke alarms for provision of minimum and maximum protection is another motivation for the research. The research looks at whether alarms in sites outside bedrooms are loud enough to wake sleeping occupants. It is recommended that to hinder the movement of smoke and slow the spread of fire, occupants sleep with their bedroom doors closed; the research looks at how this advice influences the waking effectiveness of an alarm positioned in a site outside the bedroom.

1.3 Research Goals

The aim of the research is to analyse the effectiveness of domestic smoke alarms as early warning systems by investigation of response times to the alarm signal. By activating alarms during sleeping hours, the waking effectiveness of the domestic smoke alarm can be assessed; by activating alarms during waking hours, the ability of the alarm to be heard over ambient noise can be assessed.

The research is used to determine if inexpensive smoke alarms are producing signals which are capable of alerting occupants to a fire event. The research aims to assess the advice which suggests, for maximum protection, smoke alarms should be placed in every room.

A goal of the research is to establish who is at risk of harm by not being alerted by the alarm and give recommendations as to how this risk can be minimised.

1.4 Research Limitations

Limitations to the scope of the research include sample size, bias, motivated response, alarm signal and consideration of longevity and functional effectiveness of the alarm.

Forty alarms were placed in homes in the community, reaching 128 people. The risk groups of Students, Maori and Elderly were targeted in the sample size, although each group is not mutually exclusive. There is a bias towards the student population as these comprised of predominantly postgraduate engineering students and made up over 50% of the sample population. Maori families were targeted with a bias towards homes where there were no smoke alarms installed; the elderly made up a small proportion of the selection.

The response time to the alarm signal is influenced by motivated response. The motivation results from the participants being aware of the alarm in their home and primed for its activation. There is no time for cue identification incorporated in the response time as participants are immediately familiar with the cue.

The research sets out to identify if the signal produced by the inexpensive alarm is effective at alerting occupants to a fire event. Only one type of alarm signal is investigated. No investigation is to be done to determine the longevity and functional effectiveness of the alarm. Conclusions from the research can only relay confidence in the alarm's signal, not confidence in the alarm's reliability.

1.5 Report Outline

This report intends to evaluate how effective inexpensive smoke alarms are at alerting occupants to a fire event. Background information is used to provide explanations for research methodology and techniques. Statistics highlight the hazard of domestic fires in New Zealand; risk groups are defined; current recommendations concerning smoke alarm use are given. Data from the research experiments is validated by comparison with studies in human behaviour, sleep and waking effectiveness of domestic smoke alarms. Relevant studies are outlined to provide background to the research data analysis. A critique of research into the waking effectiveness of domestic smoke alarms is given, highlighting the unique qualities of this research.

Chapter three outlines experimental procedure, the volunteers involved, apparatus used and sequence of events. The mechanism and programming of the prototype smoke alarm are described along with a classification of the alarm signal. The sequence of events, both managerial and for volunteers, is timetabled.

Results and subsequent discussion are described in chapter four. This chapter iterates the aim of the experiment by stating the hypotheses to be tested by data analysis. Limitations to the data describe where experimental uncertainties are incurred. Statistics of the base data are provided to give reference to the analysis. Response times to the alarm signal are provided and instances of 'no response' are described. Response times are compared to the variables of audibility, amount of sleep prior to the alarm and hearing impairment. The effect of ingested substances on response time latency are described as well as the influence of age on response time. Some observations link experimental procedure with human behaviour.

The final chapter gives a summary of the results, drawing conclusions from the experiments. Recommendations as to further research into the effectiveness of domestic smoke alarms are given.

CHAPTER 2: BACKGROUND

2.1 Introduction

The early stage of fire recognition is typically characterised by ambiguity (Canter, 1990); people typically respond to fire related cues by investigating their source. Ambiguity can be compounded if the cues are unclear, unfamiliar or unrecognisable The recognition of fire related cues as hazardous is also dependent on the state of mind of the investigator, their alertness, sobriety and wakefulness.

The following review highlights the problem of domestic fires in New Zealand; which groups of people are at risk and when these groups are most at risk. The review describes domestic smoke alarms, the varieties available, function and market trends. The alarm signal is described and current recommendations as to the location and installation of smoke alarms are given. Studies investigating human behaviour in fires are looked at including notes on people's reaction to smoke and fire cue recognition. To assess the waking effectiveness of the smoke alarms, an understanding of sleeping behaviour is required. Sleep is explored, looking particularly at sleep patterns, the effect of sleep on the senses and the ability of sleep to alter perceptions. To highlight the unique qualities of this research and to build an understanding of its origin, case studies on waking effectiveness are reviewed.

The resources reviewed by this literature survey are by no means exhaustive, but provide reasoning for the following research procedure and its data analysis.

2.2 Fire Hazard

Advice to install smoke alarms in family homes is driven by the proliferation and severity of domestic fires. A study of statistics from the New Zealand Fire Service's Fire Incident Reporting System (FIRS) by Irwin (1997), states that during the period 1986 to 1994 inclusive the New Zealand Fire Service attended a total of 198846 fire incidents. This equates to an average of 22100 fire incidents each year. Of the 22100 total fire incidents per year, approximately 21% were domestic (Figure 2.1).

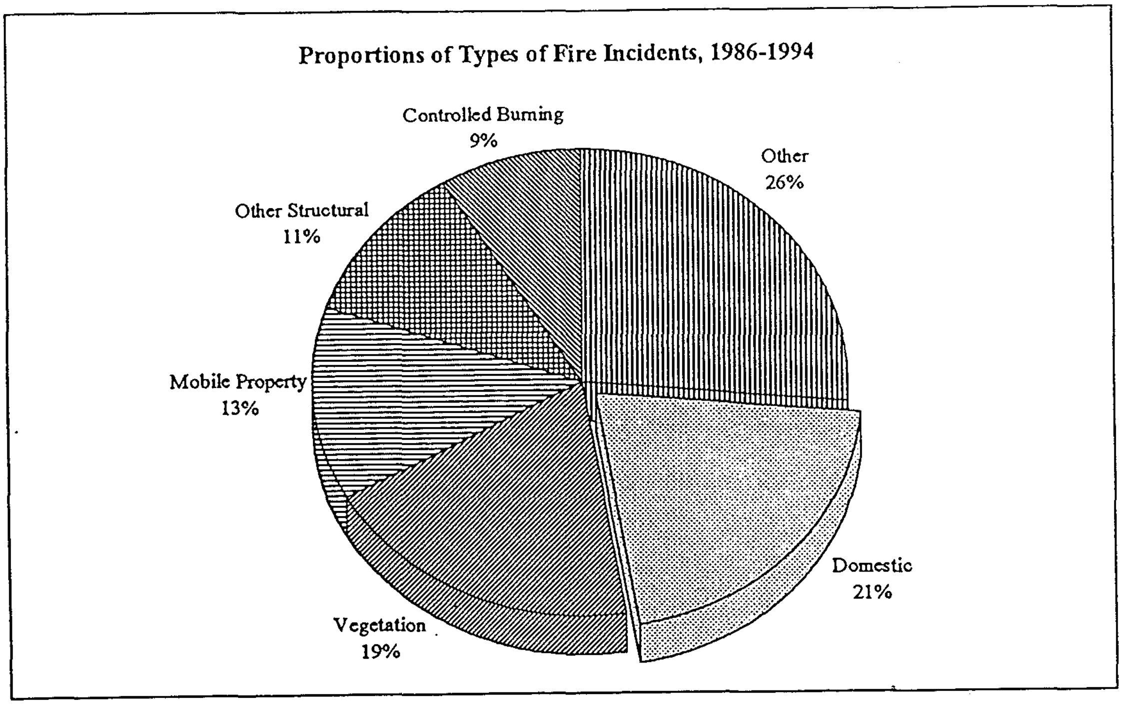


Figure 2.1: Percentages of the different areas where fires occurred over the years 1986-1994 (Reproduced from Irwin, 1997).

The following section summarises statistics concerning New Zealand's domestic fire problem. Groups particularly at risk to fire are defined, as are the times where it appears the risk of fire is heightened.

2.2.1 Domestic Fire Problem

Each year in New Zealand, approximately 5000 domestic fires occur endangering hundreds of lives. Domestic fires between the years of 1986 and 1994 inclusive, resulted in a total of 1115 civilian injuries and 170 civilian fatalities. This is an average of 124 injuries and 19 deaths each year (Irwin, 1997). From New Zealand Fire Service Statistics (1986 – 1994), Irwin (1997) concludes that for domestic fires resulting in injury, the most common area of fire origin is the kitchen and for domestic fires resulting in death, the most common area of fire origin is the bedroom. Research done by the Department of Emergency Services in Queensland on Fire Fatalities in Australia indicates that, parallel to New Zealand findings:

- Most fire death victims die before the Fire Brigade is notified
- Residential properties were the most frequently cited property in which fatal fires occurred and in particular rental properties
- The major cause of death was smoke inhalation
- The absence of smoke alarms appear to contribute to the increased risk of death in the event of a fire (FPA, 1998).

It is estimated that approximately 50% of domestic properties in New Zealand have at least one smoke alarm. Research in the United Kingdom and USA has concluded that, by providing early warning of a fire, a smoke detector can reduce the risk of residential fire death by 40 percent or more (Kuklinski et al, 1996). With 50% of homes in New Zealand lacking the early fire detection provided by smoke alarms, the hazard of domestic fires in New Zealand remains.

2.2.2 Risk Groups

Queensland Fire Fatalities Research Results conclude that the elderly, very young and adults affected by alcohol are at the greatest risk in the event of a fire (FPA, 1998). The elderly due to lack of mobility; the very young due to lack of mobility and understanding; adults affected by alcohol due to dulled senses. Correlating these risk groups with their sleeping characteristics, Grace (1997) finds that the very young have more deep sleep overall, 20 to 29 year old adults, the most probable group to have sleep influenced by alcohol, experience a high amount of deep sleep in the first half of the night and the elderly experience a disrupted sleep pattern. Irwin (1997) finds from New Zealand Statistics (1986 – 1994), the age groups with the highest fire fatality rates are the 20 - 29 year olds and the under nine year olds.

Studies abroad (Munson and Oates, 1983) and in New Zealand (Ogilvy and Mather, 1994) indicate that socio-economic factors influence the probability of a fire occurring in a domestic dwelling. Insufficient data and the qualitative nature of many variables associated with rating socio-economic status, for example the level of education, make it difficult to be conclusive on the effects of status on the probability of fire. The results of an empirical analysis performed by Munson and Oates (1983) concludes, there are relationships between the incidence of fire and the structural and socio-economic characteristics of a community; the authors suggest that a fire-prone community will have a relatively cold climate with dilapidated houses containing a high percentage of rental properties. In such a community the population would be low wage earners, have a high unemployment rate and contain a large minority population. In addition, the residents would live in overcrowded land areas and households (Munson and Oates, 1983). The study, particular to New Zealand, undertaken by Ogilvy and Mather (1994), pronounces the risk group population to be influenced by: the percentage of population aged under ten years, the percentage of population aged over 69, the income median, the percentage of unemployment, the percentage claiming benefits, the percentage of population unqualified, the percentage of rental properties, the amount of overcrowding and identification as an ethnic minority (for example, Maori or Pacific Islander).

With statistics from the United States stating homes with smoke detectors have slightly more than half the risk of incurring a death should a fire occur than homes without smoke detectors (Hall, 1994), it is implied that people in homes which do not have smoke alarms are at greater risk of injury from fire than homes with smoke alarms. Of the 50% of homes in New Zealand having at least one smoke alarm, 20% are estimated to be non-operational. Many domestic smoke alarms are disconnected due to frequent nuisance alarms or are non-operational due to inadequate maintenance. Adding the proportion of homes where the smoke alarms are not working, the number of homes at risk of fire due to no early warning system is increased to 60% - a significant risk group.

2.2.3 Time Frame

Irwin (1997) provides a graph from New Zealand statistics (1986-1994) of the number of injuries and fatalities caused by domestic fires along with the total number of domestic fires plotted by time of occurrence (Figure 2.2).

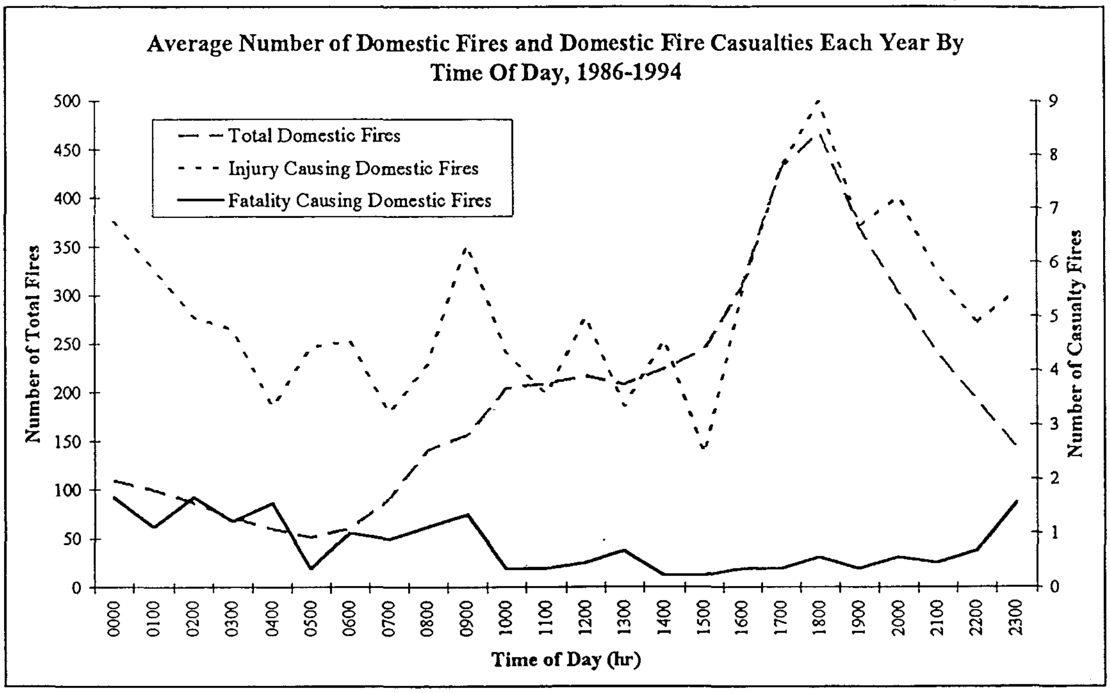


Figure 2.2: Number of injuries and fatalities caused by domestic fires along with the total number of domestic fires plotted by time of occurrence (Reproduced from Irwin, 1997).

The following trends can be gleaned from the graph, indicating the time of the day where occupants appear most at risk from a domestic fire:

- The incidence of domestic fires is relatively low during the early hours of the morning
- The incidence of domestic fires increases between 6am and 10am, coinciding with breakfast time
- The total number of fires peak between 6pm and 7pm, coinciding with dinner time
- The number of injuries caused by domestic fires peaks around 6-7pm, coinciding with the rise in total number of domestic fires
- The number of injuries caused by domestic fires peaks again around midnight
- The number of domestic fire related fatalities during the early hours of the morning is disproportionate to the number of fires occurring at the same time

The last note indicates that people are more susceptible to death from fire while sleeping (Irwin, 1997).

The day of the week also influences the likelihood of the occurrence of a domestic fire. Irwin (1997) provides a graph of the average number of domestic fires each year by day of week (1986-1994) (Figure 2.3).

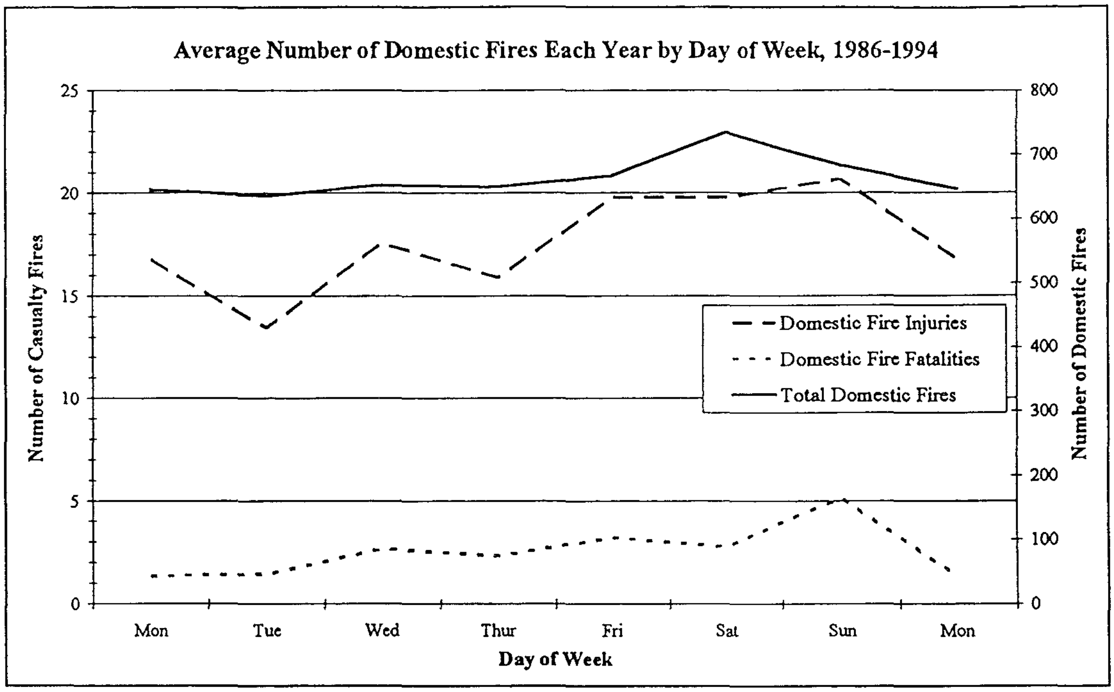


Figure 2.3: Average number of total domestic fires, injuries and fatalities occurring on each day of the week for the years 1986 to 1994 (Reproduced from Irwin, 1997).

The graph shows the days of the week where the probability of a domestic fire occurring increases. Trends of the graph show:

- The number of domestic fires occurring is at its lowest on Tuesday and there is little difference in the numbers of fires occurring between Tuesday and Thursday
- The number of domestic fires peak at the weekend - Friday night, Saturday and Sunday
- The most domestic fires occur on Saturdays
- The most injuries and fatalities caused by domestic fires occur on Sunday

The relationship between the peak number of fatalities and injuries and the peak number of fires occurring indicates there is an external factor influencing the number of fatalities (Irwin, 1997). Investigation of pre-fire activity is required to determine the influential external factor.

2.3 Domestic Smoke Alarms

For as little as $NZ8, a battery operated smoke alarm can be purchased from a hardware store, supermarket or department store. Installed properly, the alarm acts as an early detector of fire and can add valuable seconds to the escape time of an occupant from a burning building. In the absence of calculations, 2 ½ minutes is taken as the time before fire causes conditions to become life threatening (Buchanan, 1994).

The following section briefly describes the most common varieties of domestic smoke alarms, their function and available market brands. The alarm signal is investigated and current recommendations as to the installation and maintenance of smoke alarms are given.

2.3.1 Varieties

An effective household warning system integrates three elements: (1) Minimising fire hazards, (2) smoke detection equipment and (3) a family escape plan (Brennan, 1997). Minimising fire hazards and planning an escape route are issues which can be controlled by human management; smoke detection equipment is self-sufficient as long as the installation is correct and maintenance procedures are adhered to. The following gives a description of the types of smoke alarms which are in common use for domestic situations.

There are two types of smoke alarms currently available for domestic situations, the ionisation smoke alarm and the photoelectric smoke alarm. Both alarms operate by sampling the air to detect particles emitted by fire.

An ionisation smoke detector has a small amount of radioactive material in the sensing chamber (Figure 2.4). This material ionises the air, rendering the air conductive and permitting a current flow through the air between two charged electrodes. This gives the sensing chamber an effective electrical conductance. When smoke particles enter the ionisation area, they decrease the conductance of the air by attaching themselves to the ions, causing a reduction in ion mobility. The detector responds when the conductance is below a predetermined level (Bukowski, 1987).

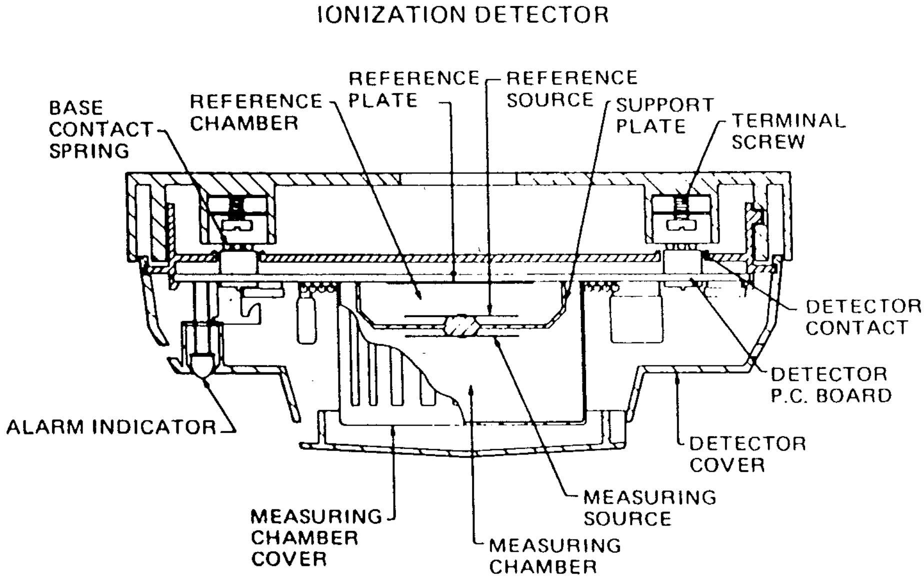


Figure 2.4: Cross section view of an ionisation smoke alarm (Reproduced from Bukowski et al, 1987).

Ionisation smoke alarms are particularly effective for domestic use as they respond to a wide variety of fires, are particularly responsive to fast flaming fires, such as that which would occur in a kitchen, and are relatively inexpensive to manufacture.

A photoelectric detector uses a small beam of light aimed at a dark corner in the light-chamber of the smoke detector (Figure 2.5). When particles of smoke get in front of the light beam, they scatter the light and reflect it onto a light sensitive photocell. The alarm sounds when an electrical current is produced after enough light is reflected onto the photocell (Irwin, 1997).

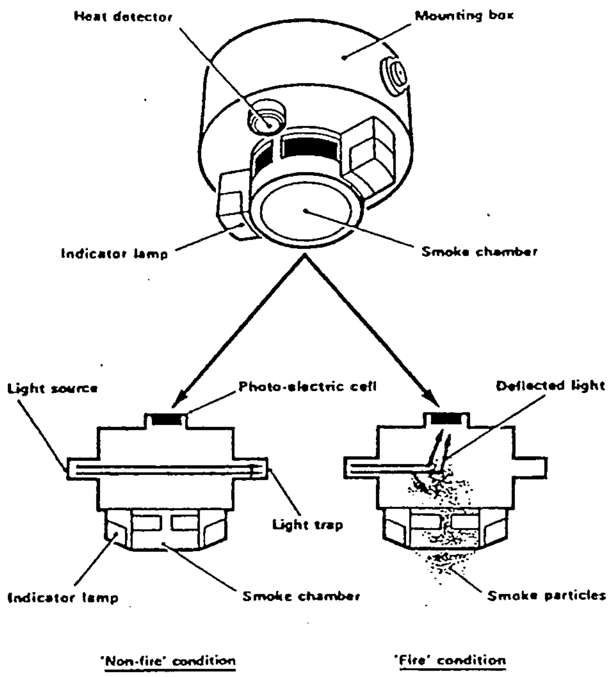


Figure 2.5:Cross section view of a photoelectric smoke alarm (Reproduced from Irwin, 1997).

Photoelectric smoke alarms, like ionisation, are particularly effective for domestic use as they respond to a wide variety of fires. The photoelectric alarms are suitable for the domestic situation as they are particularly responsive to smouldering fires and dense smoke such as that given off by foam filled furnishings (Grace, 1997).

Either the ionisation or the photoelectric smoke alarm are appropriate for use as early fire detectors in the domestic situation.

2.3.2 Function

Smoke alarms are not a guarantee against loss of life, but add valuable seconds to the time available for occupants to escape from a burning building. They do this by detecting smoke before it reaches dangerous levels (BRANZ, 1998). Similarly, heat detectors can be used as early fire detection mechanisms. Heat detectors, although a valid means of early detection, are less appropriate for use in the domestic situation due to their response time being longer than that of a smoke alarm. In the case of a smouldering fire, it may take minutes before the heat produced reaches levels high enough to be sensed by a heat detector. The sensitivity of a smoke alarm enables fires to be detected more quickly, providing occupants with more time to react either by extinguishing or escaping the fire.

Succinctly, the function of a domestic smoke alarm is to:

- detect smoke before it reaches dangerous levels;
- alert occupants to the fire.

2.3.3 Market Brands

There are a variety of stand alone domestic smoke alarms available, ranging in price from $NZ8 to $NZ50. Fifty dollar alarms include an emergency light, test button and silencer; a variety of alarms are priced between $NZ15 and $NZ25 and include a test button and silencer; for $NZ8 a basic smoke alarm can be purchased.

Public campaigns encourage the installation of inexpensive domestic smoke alarms. The ability of these $NZ8 alarms to alert occupants to a fire event serves as the impetus for the following research.

2.3.4 Signal

The choice of signal for a smoke alarm requires consideration of the environment where the alarm is to be placed. For the domestic smoke alarm, the alarm signal is required to be distinguished from ambient 'living' noise and have the ability to arouse occupants from sleep. The signal has to be unique, so as not to be misinterpreted, loud, so as to be heard over ambient noise and of the frequency and modulation to be effective at awakening occupants.

An exhaustive study of the response of a population to optimum warning signals was undertaken to find that the characteristics of optimum alerting signals were:

(1) frequency should be within the range of 700 – 4000 Hz;
(2) isolated pure tones do not have as great an alerting potential as complex signals;
(3) frequency modulation between 5% and 10% at a rate of between four and eight cycles per second increases the judged alerting potential of siren-type complex sounds;

(4) perceived loudness is the major determinant of judged alerting potential.
(Robinson, 1988)
The frequency of the signal relates to the signal's loudness and the ability of people to hear the alarm. Considerations of factors such as loss of high frequency hearing with age are required in determination of the most effective alarm signal (Robinson, 1988). LeVere et al (1973), showed that the lower frequencies had a better arousal rate than the higher frequencies.

Complex signals are stated as having a greater alerting potential than isolated pure tones. The domestic smoke alarm requires a unique signal so as to be distinguished from other alarms, for example burglar or car alarms. The uniqueness of the signal decreases the ambiguity associated with the early stages of fire cue recognition; the sound is immediately recognised as a smoke alarm allowing action to be taken.

Design criteria for sleeping occupancies state that a smoke alarm must produce a sound level 15 dBA above ambient at the pillow head (Schifility, 1995). Considerations such as whether the bedroom door is open or closed must be incorporated in design. Factors such as, the emphasis in modern construction to reduce noise using boundary treatments and increase sound transmission losses of walls and doors (Robinson, 1988), must also be considered in recommendations and advice on issues such as alarm placement and whether bedroom doors should be open or closed.

2.3.5 Recommendations

'NZS 4514:1989 The Installation of Smoke Alarms' is the New Zealand Standard dictating procedure for the installation of smoke alarms. The following are recommendations and advice associated with current smoke alarm technology from research, prevention and production sectors.

The Building Research Association of New Zealand (BRANZ) has several recommendations to make about the location and maintenance of smoke alarms:

- Always locate alarms between the living and sleeping areas of the home. If there is more than ten metres between the living and sleeping areas, or if bedrooms have a living space between them, or there is more than one floor level in the home, at least two alarms are needed to be effective;

- Mount the alarm on the ceiling or close to it – smoke spreads from top down;
- Don't place the alarm close to an opening window or other source of ventilation;
- Heavy sleep, deafness, closed doors, background noise and drug or alcohol-influenced sleep all limit the usefulness of alarms. It may be necessary to consider installing an alarm in the bedroom itself if there is danger of it not being heard;
- Test smoke alarms regularly (BRANZ, 1998).

Advice from the New Zealand Fire Service (NZFS) concerning domestic smoke alarms includes:

Choose an alarm of reputable quality identified by the prefixes:

ANSI (American National Standards Institute)

AS (Australian Standard)

BS (British Standard)

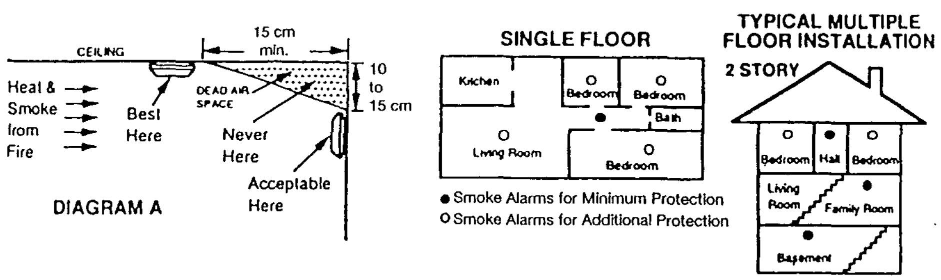
ULC (Underwriters Laboratories Canada)

ULI (Underwriters Laboratories Inc.);

Sleep with bedroom doors closed to hinder the spread of fire;

Install and maintain domestic smoke alarms according to their provided instructions.

Product labels include advice for minimum protection, alarm placed between living and sleeping areas; and for maximum protection, alarms placed in every room (excluding the kitchen) (Figure 2.6).



NOTE: THE PERFORMANCE OF SMOKE ALARMS MOUNTED ON WALLS IS UNPREDICTABLE AND THIS MOUNTING POSITION IS NOT RECOMMENDED WHEN CEILING MOUNTING CAN BE IMPLEMENTED.

Figure 2.6: Recommended locations for domestic smoke alarms (Reproduced from PDL Smoke Alarm SS 775 Instructions, 1997).

2.4 Human Behaviour

Case studies have highlighted the importance of early fire detection; the earlier the fire is detected, the more likely it is to be able to be controlled, the greater chance people have of escaping without injury. Mechanised early detection devices have increased the likelihood of fire being detected, but it is ultimately human behaviour dictating the course of action in response to fire.

The ensuing section looks into the human component in fire cue recognition and how humans react to smoke. Some studies concerning human behaviour in fire are investigated with particular attention paid to human behaviour when aroused from sleep.

2.4.1 Recognition of Cues

Reaction of humans to fire can be categorised into three stages: (Grace, 1997)

(1) Interpretation
(2) Preparation
(3) Action

Important in the sequence of events in response to fire is the first phase, interpretation. Interpretation involves the individual receiving information, recognising it as a fire cue then investigating or misinterpreting the cue. Correct recognition of fire cues is dependent on:

- Cue Intensity; the louder, brighter larger, more rapidly rising or otherwise more potent the cue the more likely its detection;
- Cue Salience; more important stimuli are more apt to be noted;
- Focus of Attention; a person engaged in an engrossing task is less likely to detect a cue from the environment;
- Drugged versus Undrugged; barbiturates tend to raise detection thresholds, amphetamines to lower them;
- Asleep versus Awake; Sleeping subjects are less apt to respond to equal stimuli than awake subjects (Kahn, 1984).

Cue ambiguity features as a major cause of delay in reaction to fire. Ambiguity causes misinterpretation of cues, increasing detection time, leaving less time for decision making and action. Canter (1990) factors misinterpretation of fire cues strongly into his decomposition diagram. The decomposition diagram attaches probabilities of occurrence to the sequence of events of a fire scenario (Figure 2.7).

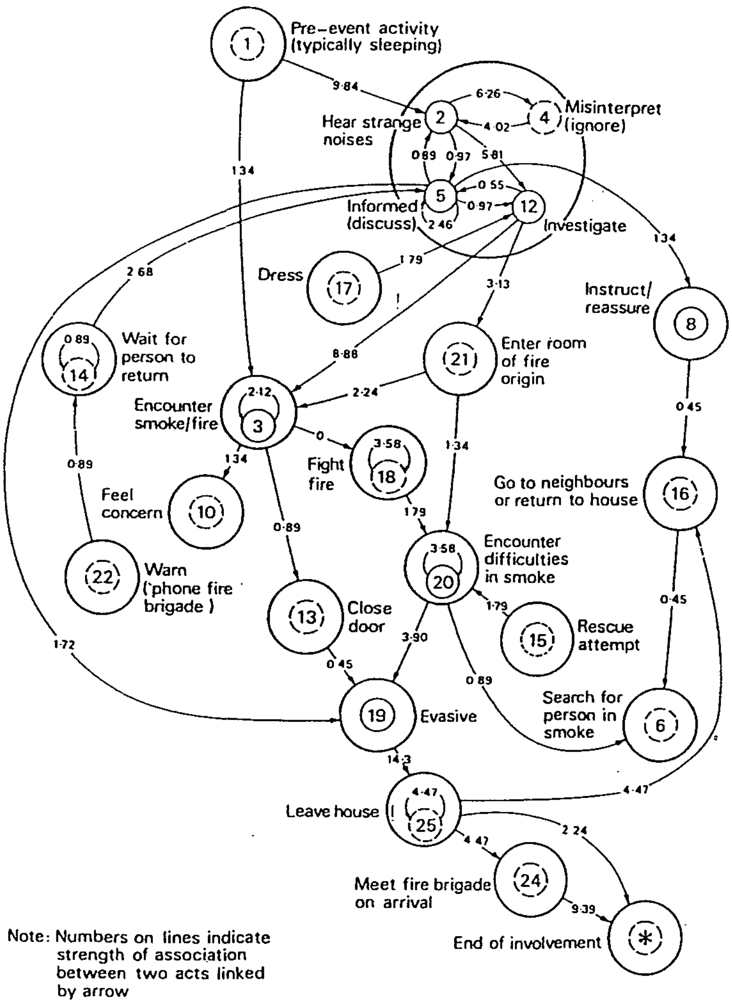


Figure 2.7: Decomposition Diagram (Reproduced from Grace, 1997).

People rely on information from others to clarify their interpretation of the cues. Seeking confirmation of cue interpretation factors into the delay time as shown by the decomposition diagram. Cue ambiguity in the domestic situation can be minimised by use of smoke alarms when residents are familiar with their distinctive signal.

2.4.2 Reaction to Smoke

Research into the body's ability to smell smoke when asleep debates that a person's sense of smell is dulled while asleep. Experiments using smoke odour as a stimulus show that the smell of smoke does not reliably arouse people from sleep. While it is proven that, while asleep, the ability to register smells is diminished, no research has been done into the influence of irritations associated with smoke on arousal from sleep. The irritation of heat and smoke particles as opposed to smoke odour, may be the factors which arouse people from sleep.

2.5 Sleep

Sleep is not a state of unconsciousness but rather, a dynamic process of alternating physiological lulls and turbulences, an ongoing progression of rhythmic cycles reflecting different phases of neural functioning with varying sensory thresholds (Nober et al, 1981).

The following section briefly describes sleep patterns, factors affecting awakenings and the idea of motivated response.

2.5.1 Patterns

Grace (1997) describes the sleep characteristics of humans, showing the difference in sleep patterns with age and gender. In summary, the following sleep patterns influence the waking effectiveness of domestic smoke alarms:

(1) Stage of sleep; there are three behavioural sleeping states, wakefulness (W), rapid eye movement (REM) and non-rapid eye movement (NREM). Each stage of sleep is indicative of a depth of sleep which in turn affects the ability to be woken. Stages of sleep, their characteristics and waking potential are summarised by the following table (Table 2.1).

Table 2.1: Sleep Stages.

		NREM				
Sleep stage	W	Stage 1	Stage 2	Stage 3	Stage 4	REM
Characteristic	Person fully awake	Person falling asleep 1-7 minutes	Onset of sleep	Transient between 2 and 4	Deepest stage of sleep	Intense dreaming and REM
Wakening Potential		Easily woken	Person sound asleep, easily woken	Intense noise required to awaken person	More intense stimulant to waken person	
NREM – a relatively inactive yet actively regulated brain in a moveable body REM – a highly activated brain in a paralysed body (Grace 1997 chapter 2)						

(2) Age; age influences the period of time spent in each stage of sleep. Grace (1997) concludes:

- 20 – 29 year olds experience a high amount of deep sleep in the first half of the night, requiring an intense noise to be woken
- Under nine year olds experience the most deep sleep over all
- 70 – 80 year olds experience a disrupted sleep pattern with a low amount of deep sleep (stages 3 and 4) and continuous awakenings.

2.5.2 Awakening Influences

Sleeping patterns can be influenced by external factors such as alcohol, medication and sleep deprivation. The factors re-proportion the time spent in each sleeping stage. Increasing the time spent in a deep sleep stage is of detrimental effect to the waking effectiveness of domestic smoke alarms. Factors which particularly influence awakening include:

- Drugs and Alcohol, by increasing the amount of deep sleep, particularly in the first couple of hours, and impairing performance such as reaction time and motor coordination (Grace 1997).
- Sleep Deprivation, by increasing the amount of stages 3 and 4 (deep) sleep.

Audibility of the alarm at pillow level affects the ability of the smoke alarm to awaken. External factors such as whether the bedroom door is open or closed and the distance between the alarm and the bedroom, influence the perceived loudness of the alarm and hence its ability to wake. Research shows that sounds can often be incorporated into dreams. By combining the dreaming stage of sleep with the alarm signal, sound incorporation into dreams can slow the waking effectiveness of the smoke alarm.

2.5.3 Motivated Response

Motivated response occurs when a sleeping subject is primed to respond to a known stimulus; for example, a doctor on call responding to the ring of the telephone, a mother responding to the cry of her child. Grace (1997) looks in depth at motivational responses and their effect on response to alarm signals. Of particular interest to the waking effectiveness of domestic smoke alarms includes the ideas of the ability to discriminate between familiar and unfamiliar sounds while asleep and the effect of emotional content on the waking effectiveness.

Research has shown that people have the ability to discriminate between sounds while asleep. A study was done using a person's name as the stimulus for response. It was found that subjects responded more often to their own name than any other name (Grace 1997). Sleepers can, if familiar with the signal, be primed to respond to the sound of a smoke alarm.

The more emotional content associated with the stimulus, the more effective the stimulus is at awakening people from sleep. If there is an incentive to responding to the sound, whether for personal gain, such as monetary, or personal concern, such as a crying baby, a person can be motivated to respond. Grace (1997) concludes, that a person can set themselves the task of awakening to some particular stimulus and can in fact, succeed in that task to some extent.

2.6 Waking Effectiveness – a literature survey

A variety of studies have been done, evaluating the effectiveness of domestic smoke alarms. Some studies investigate the waking effectiveness of smoke alarms in controlled environments, others utilise the familiar home setting as a forum for their investigations. The following is a critique of some prominent research concerning topics investigating the waking effectiveness of domestic smoke alarms.

2.6.1 Case Studies

- Study 1: Non-arousal and Non-action of Normal Sleepers in Response to a Smoke Detector Alarm (Bruck, 1995)

In this study, twenty-four young adults were exposed twice to a smoke detector alarm activated of 60 dBA at pillow level. The participants were in a controlled sleeping environment and were unprepared for the first alarm activation. Results of the experiment show that:

i) 20% did not reliably awaken to the alarm with this being associated with a reported lack of sleep the night before

ii) of the awakenings, 87% occurred within one minute

iii) when awoken by the first alarm signal, 95% took no action and 92% did not correctly interpret the alarm nature of the signal.

Conclusions from the experiment include:

i) Sleep deprivation appears to increase the probability of not awakening

ii) Emphasis must be given to the importance of smoke alarms being installed close to the bedside and further studies of arousal in such circumstances conducted

iii) The alarm signal must be more recognisable as a fire cue.

- Study 2: Non-awakening in children in response to a smoke detector alarm (Bruck, 1998)

Twenty juniors, aged six to 17 years, and their parents, aged 30 – 50 years, were exposed, on two different nights in their own homes, to an alarm which sounded 60 dBA at the pillow. The sleeping participants were asked to respond to the alarm signal by activating a wrist actigraph and completing a questionnaire. Results of the experiment show:

i) 85% of the juniors slept through one or both of the alarms, 100% of the adults reliably woke

ii) where a participant awoke, 95% awoke within 32 seconds of alarm activation

iii) on average, those who awoke reported being clear-headed

Research concludes that smoke alarms need to be interconnected. This recommendation is in line with previous research considering the optimum location of alarms which suggests that the best location for an alarm is not necessarily the best location for a detector.

Data currently being collected at Victoria University of Technology in Melbourne, Australia, hopes to establish whether children aged between 6 and fifteen years will reliably wake when a smoke alarm of 85 – 90 dBA sounds in their own bedroom.

- Study 3: Waking Effectiveness of Household Smoke and Fire Detection Devices (Nober et al, 1981)

This study correlates the waking effectiveness of domestic smoke alarms to the sensory threshold variations associated with the stages of sleep. Three experiments were designed to determine the waking effectiveness of a taped smoke detector alarm signal. There were three alarm signals presented to three groups of volunteers; 55 dBA, 70 dBA and 85 dBA. The alarms were presented to the volunteers once over a seven day instalment period in their own home. The volunteers were required to shut off the alarm signal and telephone the fire department. Conclusions from the experiment include:

i) The three detector alarm signals (55 dBA, 70 dBA, 85 dBA) were loud enough to awaken normal-hearing college-age adults from sleep at varying hours of the night.

ii) In the alarm-alone conditon, shut off latency was significantly slower in the 55 dBA condition than in either the 70 dBA and 85 dBA condition. Shut-off latencies did not significantly differ between 70 dBA and 85 dBA. Variables of sex, time of night and day of week did not yield significantly different response magnitudes.

iii) A taped 63 dBA noise from an air conditioner significantly increased the waking latency at the 55 dBA and the 70 dBA alarm levels, compared to the quiet conditions and the VCR-TV experimental conditions.

iv) Subjects who were awake watching a video when the alarm sounded responded with the shortest latency, shut-off time at both the 55 dBA and 70 dBA alarm levels.

v) With appropriate motivation and sensitisation normal-hearing young subjects can be awakened from sleep and expected to perform coherent tasks with a detector alarm at 55 dBA in a quiet setting. At 70 dBA, subjects in the quiet and with the background air conditioner noise were awakened.

vi) Questionnaire data generally showed that subjects accurately projected whether they were light or heavy sleepers and would be awakened rapidly by the detector alarm signal. Subjects who reported that their sleep tended to be interrupted and subjects who reported that they played radio or TV sets in their bedrooms prior to sleep, generally awakened faster than subjects who did not make these reports.

- Study 4: Will Your Smoke Detector Wake You? (Berry, 1978)

This study looks into the ability of a stand-alone smoke alarm, situated outside the bedroom, to wake sleeping occupants. The research argues that attenuation causes the alarms to be so dulled that their signal, when reaching the pillow, is less than the required 15 dBA above ambient. An awakening worksheet is developed to determine the probability of awakening from sleep, given smoke detector activation. The worksheet is to be used to determine if a smoke alarm in a site outside the bedroom is loud enough to wake, factoring into consideration attenuation losses due to distance, open or closed doors, number of walls and number of storeys. Research recommends that a stand-alone smoke alarm, remote from the sleeping areas, is not always sufficient to awaken. It is recommended that the awakening worksheet be used to determine the number an location of smoke alarms.

- Study 5: Reliability and Effectiveness of Domestic Smoke Alarms (Marriot, 1995)

A study was undertaken in England and Wales to determine how well smoke alarms are maintained by the householder once installed. Statistics show that the number of households owning one or more smoke alarm is increasing, but little is know about how well these smoke alarms are maintained once installed. This study, by distributing and monitoring ten thousand smoke alarms over a three year period, set out to prove how reliable the domestic smoke alarm is. Results show that 89% of the smoke alarms were still serviceable at the end of three years suggesting that domestic smoke alarms, in general, are well maintained. The study highlighted inadequacies in:

i) the method of cleaning smoke alarms

ii) the need for annual battery replacement

iii) the meaning of the low battery warning signal

iv) understanding the need for regular testing

v) the level of protection afforded by fitting only one smoke alarm per dwelling and the added level of protection attainable by fitting more.

- Study 6: Smoke alarms fitted on ground floors may not be loud enough for sleepers (*FIRE*, 1992)

It is unfortunate that most smoke alarms are bought only if they are very cheap and are then unlikely to have interconnection facilities. This article, from the United Kingdom , highlights the concern that cheap, stand-alone smoke alarms may not be able to produce a sound loud enough to be heard in a room remote from the device, particularly in a room upstairs. Experiments were carried out to determine if an alarm, situated in a hallway downstairs, could be heard in a bedroom upstairs. Sound pressure measurements were taken and results show that sound levels in the bedroom were not reaching the 15 dBA above ambient level stated as required for waking sleeping occupants. Results also show the effect furnishings have on reducing sound attenuation. The research concludes that, in order to be effective, smoke alarms must be interconnected and sound simultaneously. The research recommends that the inexpensive smoke alarms, although they work, are inadequate if not interconnected.

- Study 7: U.S. Research on Body's Ability to Smell Smoke when Asleep (STAR, 1998)

Opinions were split between whether smoke stirred victims from sleep or whether a depressed sense of smell prevented this from happening. A study set out to prove if smoke odour had the ability to awaken people from sleep. Ten subjects were exposed to a non-threatening smoke odour while asleep in a controlled environment. The exposure was administered to the participants at the same stage of sleep and lasted 90 seconds. Two of the ten subjects were aroused from sleep by the smoke odour. The research concluded that, fire detection and suppression alarms are the only prudent method of alerting sleeping persons to a fire in their homes.

- Study 8: Improving the Waking Effectiveness of Alarms in Residential Areas (Grace, 1997)

Thomas Grace's report, The Waking Effectiveness of Alarms in Residential Areas, is referenced several times in the preceding sections. Statistics and information provided by this Canterbury University Masters in Fire Engineering Research Report, form the basis for a significant part of the following research analysis. The statistics provided are particular to New Zealand; the information provided strongly links sleeping characteristics to the waking effectiveness of domestic smoke alarms. Grace (1997) succinctly references waking effectiveness literature and studies.

Some studies have been done in the United States which investigate the benefits to having a domestic smoke detector installed. Studies include: a cost-benefit analysis of domestic smoke alarms (Spearpoint, 1997), a probe into the reasons for smoke detector nuisance alarms particularly in the Native American community (Kuklinski et al, 1996), publishing of data recording the U.S. experience with the introduction of domestic smoke alarms (Hall, 1994). Kahn (1984) looks at human awakening and its effect on identification of fire related cues, highlighting how fire related cues can be ambiguous. Information from these studies can be applied to the New Zealand situation to gain an idea of the broader benefits of installing smoke alarms in private homes.

2.7 Summary

The research aims to determine whether inexpensive smoke alarms are effective at alerting occupants to a fire event. Statistics specific to New Zealand are used to devise an experiment which investigates human behaviour in response to a smoke alarm signal. Previous studies have been done which look at the waking effectiveness of the domestic smoke alarm with this research building on established conclusions. The following section highlights the unique qualities of this research.

2.7.1 Research Differences

Although a variety of studies have been done which investigate the waking effectiveness of domestic smoke alarms, this research brings a new perspective to the study as it looks particularly from the New Zealand viewpoint. Other research has looked at what decibel level is optimal for alerting occupants, rather than investigating the question, does what is out there work? Factors which create the uniqueness of the research are the study environment, choice of participants, time choice of alarm events and the alerting device mechanism.

New Zealand fire incidence and fatality statistics determined choice of participants and time of alarm activation. The statistics used are unique to the risk of a domestic fire in New Zealand.

Development of the computer operated alerting device is unique to the experiment. The device adds a dimension of authenticity to the research as the actual alarm is used, not a recorded signal.

CHAPTER 3: PROCEDURE

3.1 Introduction

An experiment was devised to investigate the effectiveness of the inexpensive domestic smoke alarm signal at alerting occupants to a fire event. The experiment involved fabricating an alerting device to sound an alarm, identical to that of a domestic smoke alarm, at predetermined times between 6pm and 6am. Volunteers from the risk groups of students, Maori and elderly participated for two weeks in the experiment by allowing an alerting device to be installed in their home and responding to three alarm calls. Data from the experiment is used to examine response times to the alarm signal and identify who is particularly at risk to harm from fire. Analysis of the data from the experiment aims to conclude if inexpensive smoke alarms are effective at alerting occupants to a fire event.

The following section outlines the experimental procedure. The risk groups involved in the research are named and their selection procedure explained. Demographics of the volunteers involved in the experiment, are described. The alerting device, its mechanism, circuit and signal are described and the audibility recording instruments explained. A sequence of events of the experimental procedure is provided to timetable and document the procedure practiced.

3.2 Subjects

A research brief and details of volunteer involvement were advertised to student, Maori and elderly groups. Response to the advertisement resulted in forty homes volunteering to participate in the smoke alarm study. All volunteers received a complementary smoke alarm for participating.

3.2.1 Risk Groups

The risk groups of students, Maori and elderly were determined by New Zealand's fire incidence and fatality statistics. The three particular risk groups were chosen due to the higher probability of occurrence of a fire starting in their homes. The groups are not mutually exclusive, neither are they truly representative of a cross section of New Zealand's community.

3.2.2 Selection Procedure

All subjects volunteered to participate in the experiment. The student group was chosen from predominantly postgraduate engineers, with flatting situations preferred. A university lecturer, with two young children, was added to the student group for a specific investigation of the response of under ten year olds to the smoke alarm. A contact from Ngai Tahu, Christchurch's local iwi, selected Maori volunteers. Preference was given to Maori families without a smoke alarm installed in their home. Elderly volunteers were chosen from response to an advertisement in a local club's newsletter.

3.2.3 Demographics

The volunteers are split into two groups, the primary group and the total group. The primary group comprises of the principal members of each household. The principal member is defined as the spokesperson for the home. Additional information, such as type of sleeper and history of hearing impairment, is provided by the principal members for further investigation into response time latency. The principal member is the main respondent to the alarm. The total group comprises of all the people who experienced an alarm event.

Forty homes participated in the study: 26 from the student group, 10 from the Maori group, 4 from the elderly group (Figure 3.1).

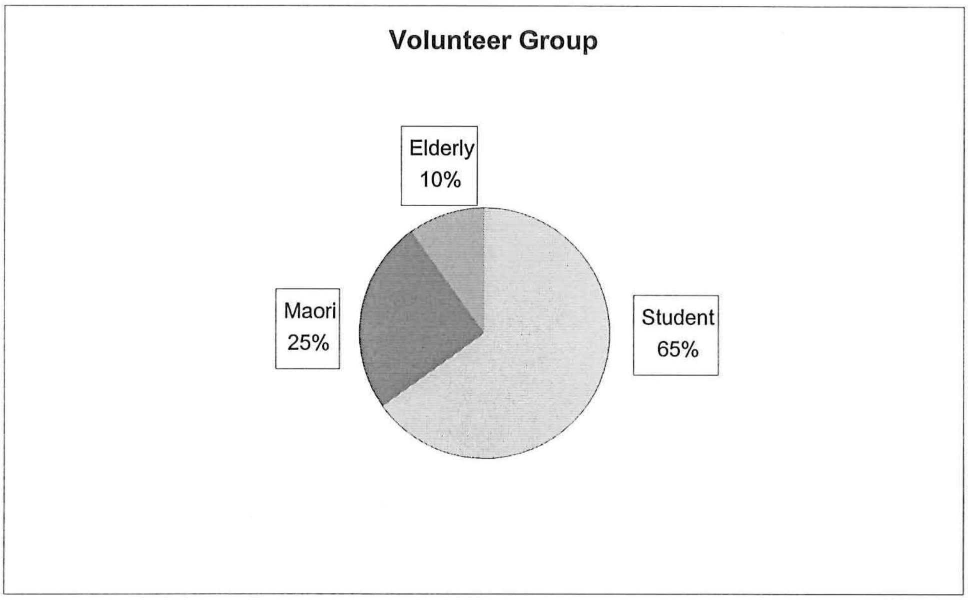


Figure 3.1: Distribution of volunteer group.

The primary group is comprised of 40 subjects aged between 21 and 79, with 13 females and 27 males (Figure 3.2).

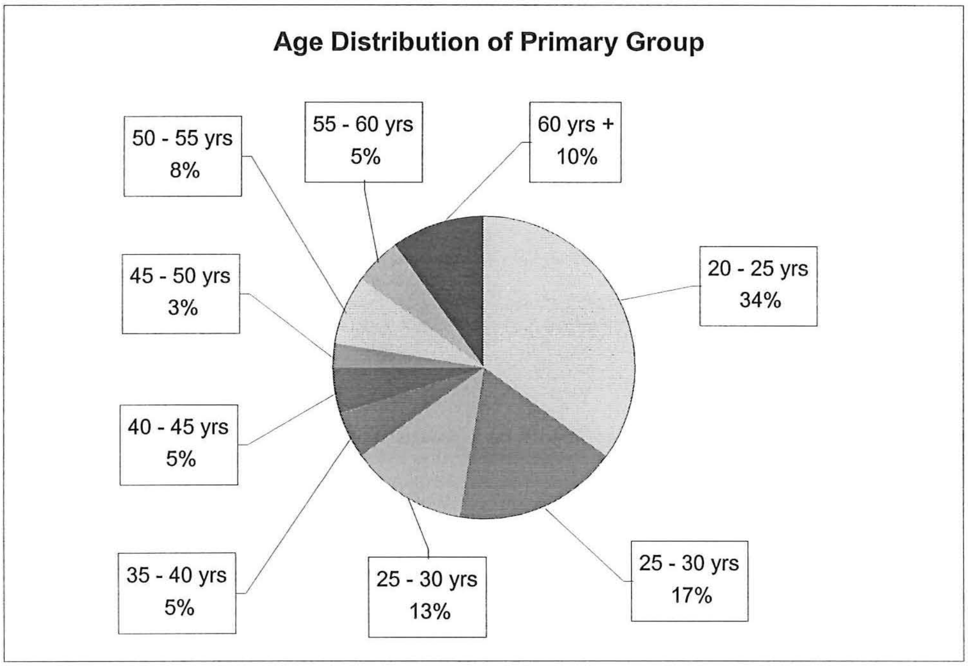


Figure 3.2: Age distribution of primary group.

128 subjects aged between one and 79, with 61 females and 67 males, participated in the study and experienced at least one alarm event (Figure 3.3).

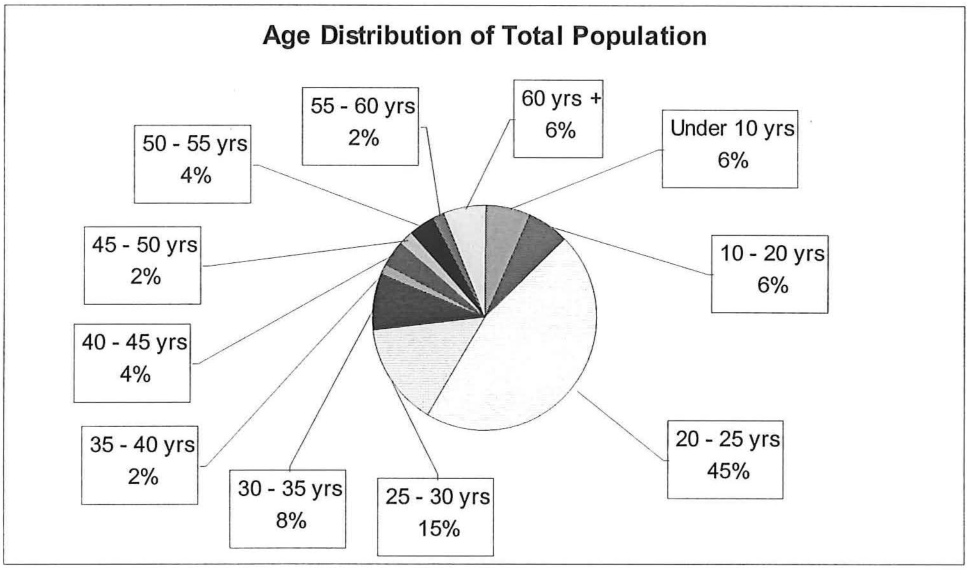


Figure 3.3: Age distribution of total population.

3.3 Alerting Device

To enable an alarm signal to sound independently at a known date and time, a computer operated smoke alarm mechanism was required. The alerting device was required to be portable, programmable and piercing to meet the criteria of the experiment. Portable, with an independent power source and to enable easy instalment; programmable, with the ability to recall dates and times of alarm events and record data of response times; piercing, having an alarm signal the same as that of the inexpensive domestic smoke alarm. It was decided to adapt an existing domestic smoke alarm to meet these criteria. Twenty five alerting devices were made.

3.3.1 Mechanism

An eight dollar, ionisation smoke alarm was adapted for use as a computer operated alerting device (Figure 3.4). The internal workings of the smoke alarm were removed, leaving only the sounding device. Removal of the radioactive ionisation chamber rendered the smoke alarm unusable as a smoke detector, with this point being stressed to the volunteers. The contents of the smoke alarm case were replaced with a computer circuit (Figure 3.5). The computer circuit has programming capacity, enabling dates and times of alarm events to be stored. When the programmed time of the alarm event is reached, the alerting device sounds an alarm of the same signal as a domestic smoke alarm; the alarm is deactivated when switched off by the volunteer. The computer records the time difference between activation and deactivation and this time is recognised as the response time to the alarm signal. If not responded to, the alerting device automatically deactivates after 255 seconds. Information from the alerting device can be downloaded into a computer program devised for the experiment.

Figure 3.4: Alerting device.

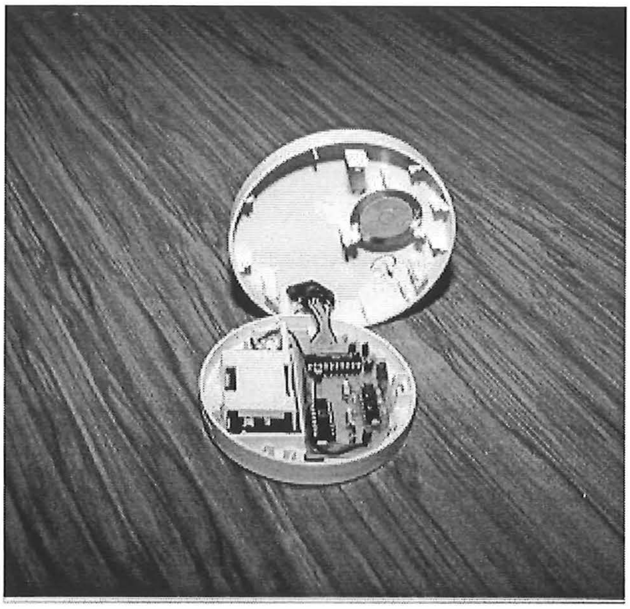


Figure 3.5: Internal workings of alerting device.

3.3.2 Circuit Description

The following is a description of the computer circuit used in the experiment (Figure 3.6). The workings of the alerting device are explained by Michael Weavers, electronics technician responsible for adapting the domestic smoke alarm into a computerised alerting device.

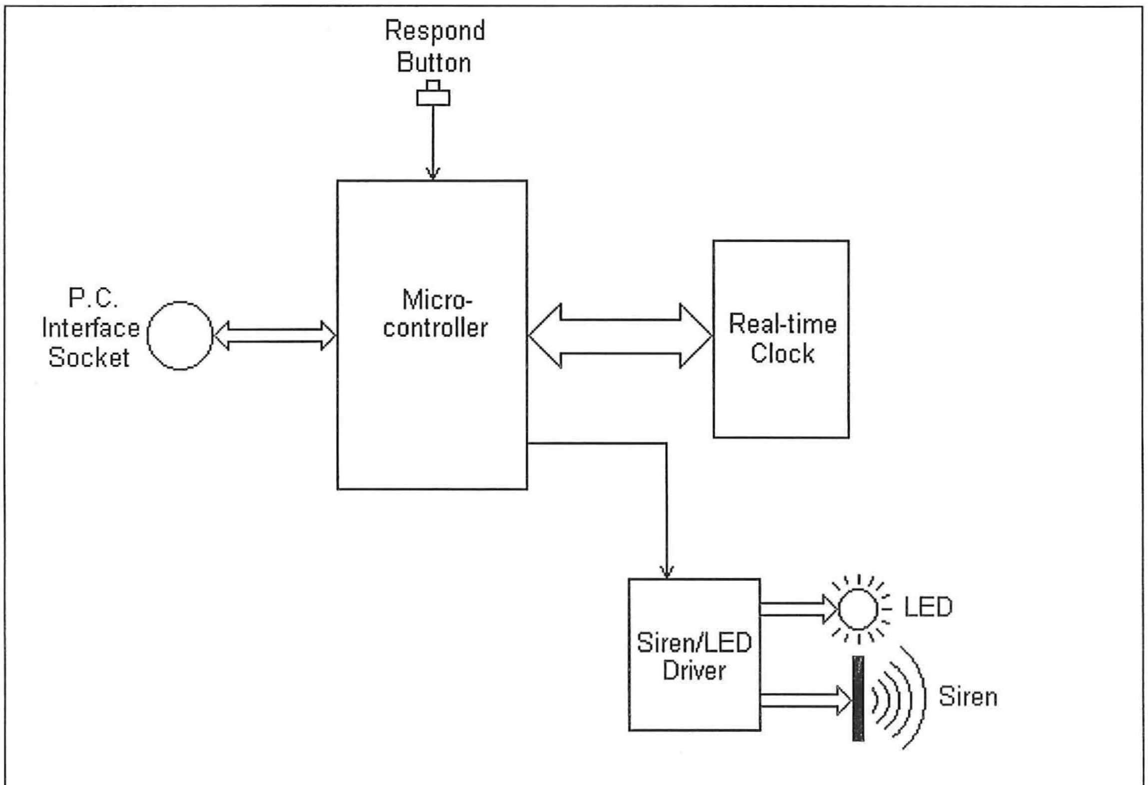


Figure 3.6: Circuit diagram of alerting device mechanism.

The core of the alerting device consists of a Microprocessor (μP) chip and a Real-Time Clock (RTC) chip. The μP has a serial interface which receives commands/data from a computer running loading software devised for the experiment. These commands, sent from the host computer via a small RS232 interface cable to the μP, allow the RTC's current time and the stored individual alarm times to be set. The μP has the capacity to store four alarm events in its memory.

Normally the μP is in 'sleep' mode to conserve power. Four things can 'wake' the μP: (1) a power-up, (2) the serial interface being plugged in, (3) the RTC's alarm going off, (4) the stroke of midnight. On power-up, the μP initialises the RTC so that it 'wakes' the μP at the stroke of midnight every night. The μP also initialises a status register and resets all variables. When the serial interface is plugged in, the μP 'wakes' to receive commands/data from the host computer. The four alarm dates and times are downloaded into the μP, along with the current date and time; the serial interface is then unplugged. Upon disconnection of the serial interface, the μP checks the first alarm to see if it is for today and if so, it loads that alarm hour and minute into the RTC and enables the RTC's alarm. If the alarm is not for today, the μP leaves the RTC's alarm disabled. The μP then goes back to 'sleep'. On the stroke of midnight, the RTC 'wakes' the μP to check if the next alarm is for that new day. The μP checks a register to see which alarms have already gone off and which one is next in line. The μP then checks if the next alarm's month and date match today's month and date. If times match, the μP loads that alarm hour and minute into the RTC and enables the RTC's alarm. If alarm times do not match, the μP leaves the RTC's alarm disabled. After this day preparation, the μP goes back to 'sleep'.

When that day's alarm time matches the real time of day, the RTC 'wakes' the μP which turns the alarm sounder on and begins counting seconds. The μP monitors the alerting device's silencer button and as soon as the user presses it, the μP turns the sounder off and stops counting seconds. The response time in seconds is then stored in memory. If the silencer button is not pressed within 255 seconds, the μP turns off the sounder and stores 255 seconds for the response time. The μP then updates the status register to indicate that alarm 'n' has gone off and checks if the next alarm is for the same day, loading it if so. If not the μP disables the RTC's alarm. The μP then goes back to 'sleep'.

When the fourth alarm has gone off, the μP disables the midnight 'wake-up' as well as the alarm and goes to 'sleep' until the next power-up or serial interface connection

3.3.3 Signal

The alerting device required an alarm signal identical to that sounded from an inexpensive domestic smoke alarm. It was decided to use the sounder from an eight dollar, ionisation smoke alarm. Adapting an existing smoke alarm to make the alerting device enabled the sound achieved to be identical to that of a domestic smoke alarm as the buzzer and subsequent resonance from the device are the same.

The inexpensive smoke alarm and subsequently the alerting device, produce a pulsing alarm signal. The alarm, at the source, produces a maximum sound of 110 dBA.

The alarm signal repeats at a frequency of four 'beeps' per second (Figure 3.7).

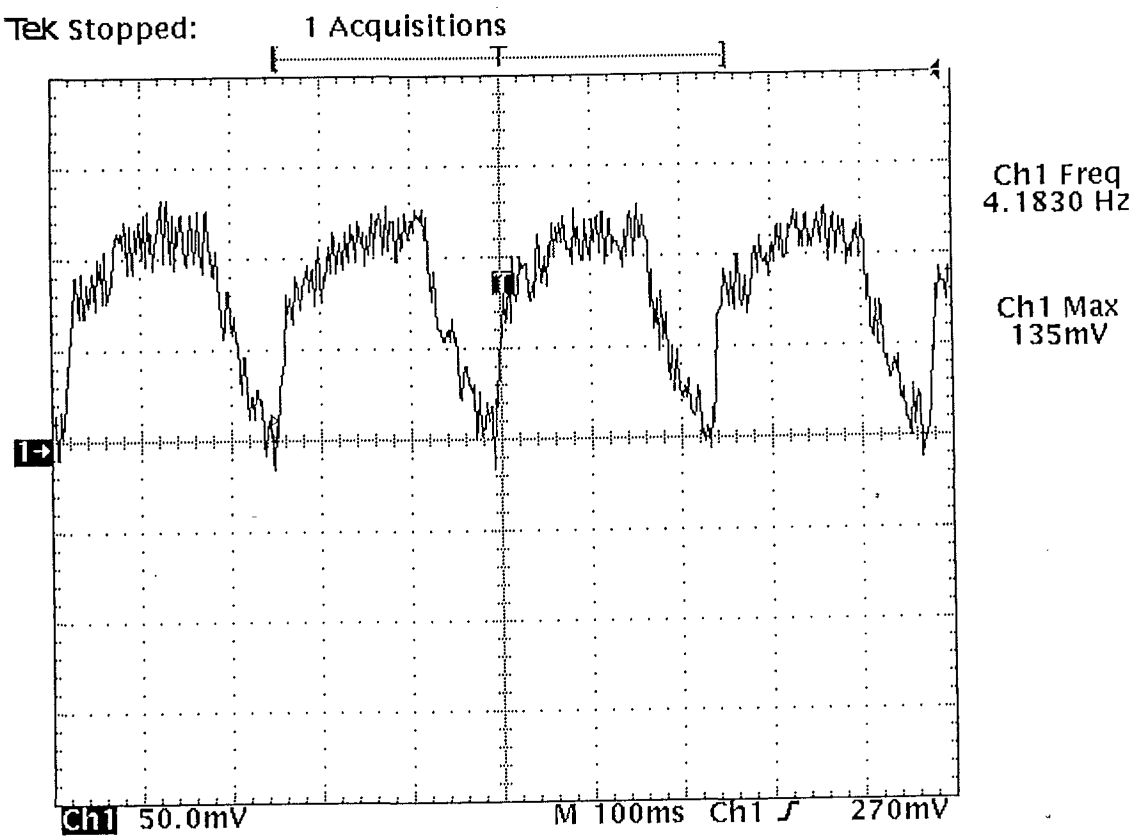


Figure 3.7: Alarm signal.

The pitch of the alarm is approximately three kilohertz, at the source (Figure 3.8).

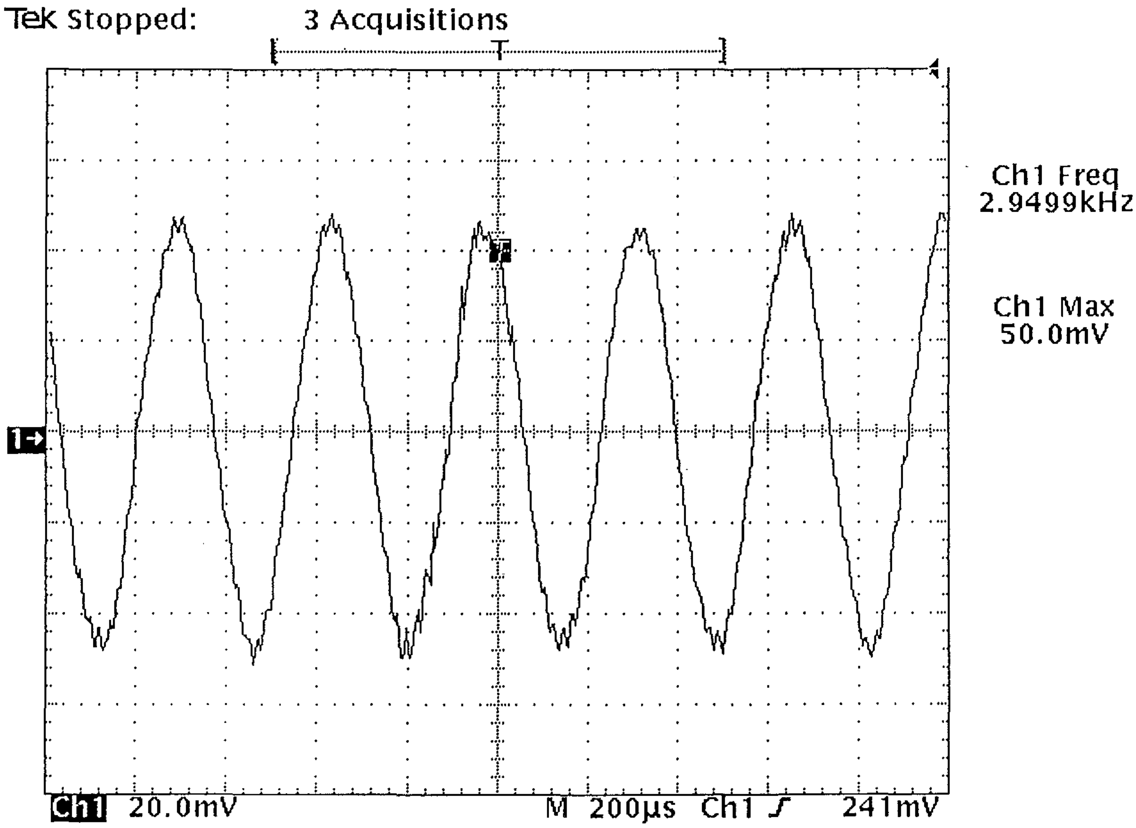


Figure 3.8: Alarm signal pitch.

The alarm signal used for the alerting device has the characteristics of an alarm suitable for waking sleeping occupants and alerting occupants to a fire event. The alarm is a complex signal with greater alerting potential than an isolated pure tone; the pitch of the alarm signal (3kHz) has a frequency within the limits determined optimal for greatest alerting potential (700Hz-4kHz); the alarm signal is unique, varying from those used for household alarms such as security and car alarms.

3.4 Audibility

Measurements of the audibility of the alerting device were required to be taken in the bedrooms of each home. The audibility was needed to compare the volume of the smoke alarm with its waking effectiveness and subsequent response times. The general unit for measurement of sound pressure levels are A-weighted decibels (dBA).

3.4.1 Apparatus

A hand-held sound level meter was used to record the smoke alarm signal (Figure 3.9). The battery operated device has two scales, low and high, with the ability to pick up sounds ranging from 40 to 120 dBA. The sound meter is linked to a peak level meter which measures the sound level in of the smoke alarm in millivolts.

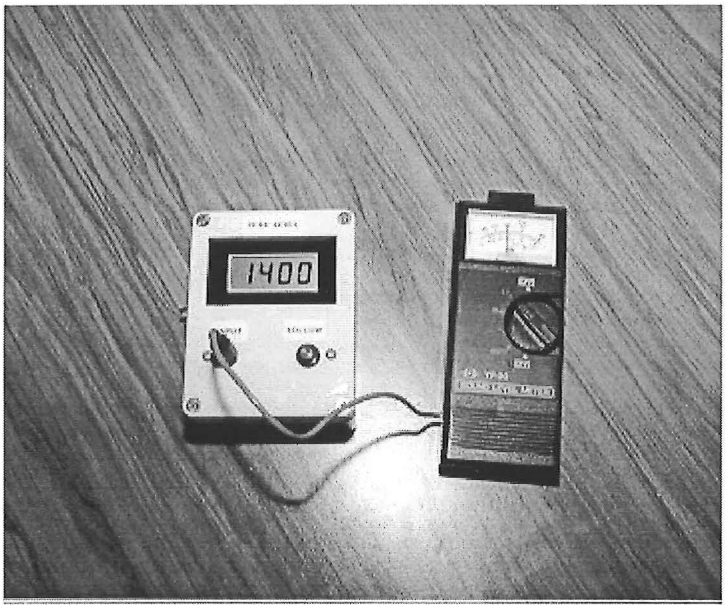


Figure 3.9: Peak level meter (left) and sound level meter.

3.4.2 Calibration

Due to the resolution of the scale in the sound meter and the pulsing signal of the alarm causing the needle of the sound level meter to fluctuate, readings of the peak level sound produced by the alerting device were taken from the peak level meter and converted from millivolts to decibels (Figure 3.10). Five readings of the peak sound level (millivolts) were averaged, then converted to decibels using a calibration. The sound level meter and the peak level meter were calibrated by producing a pure tone of a known decibel level in a quiet room. The peak level reading in millivolts was taken, corresponding to the decibel level. The results of the calibration were graphed and a polynomial trend-line fitted. The equation of the trend-line was used to convert the average millivolt reading to decibels.

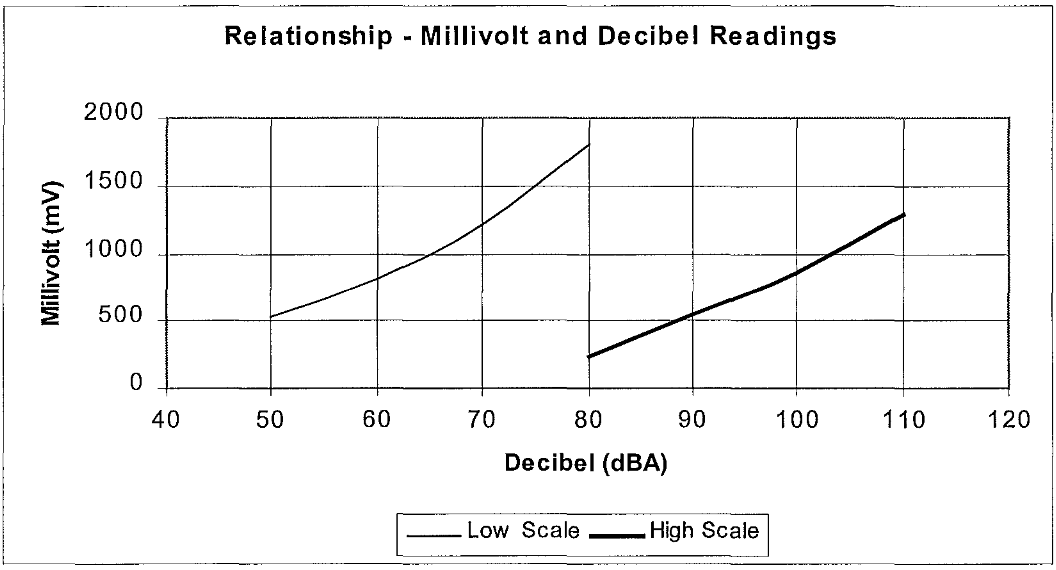


Figure 3.10: Graph of relationship between millivolt and decibel readings of audibility.

3.5 Sequence of Events

Experimental procedure can be split into three sections, preliminary work, alarm events and post-alarm events. The three sections can each be split in two parts, actions of the researcher and actions of the volunteer. Preliminary work involves the researcher planning the number, date and time of each alarm event. The researcher is required to install each alarm, take audibility readings of the alarm in each volunteer's bedroom and record details of the occupants in each volunteer household. Prior to the alarm event, volunteers are briefed on experimental procedure and details pertaining to occupants in the home, are recorded. Each alarm event sees the volunteer responding to the alarm and the researcher recording the response on an answer machine. Post-alarm questioning is done the day following the alarm event. The alerting device is collected by the researcher at the end of the two week experimental period.

The following section describes the sequence of events involving the researcher and volunteer in the waking effectiveness experiment.

3.5.1 Alerting Device Activation

The experimental period ran from November 1, 1998 to December 23, 1998. Each volunteer household had an alerting device installed for two weeks. The device was set to activate three times during the two weeks, once in the early evening and twice during the night. The alarm events were programmed to occur between 6pm and 6am, with one alarm occurring in each of the time segments, 6pm-10pm, 10pm-2am and 2am-6am, for each household. The three time segments were chosen to correspond with the peak time of fire occurrence. 6pm-10pm, the early evening time frame, was chosen to correspond with dinner and family times; a generally noisy time of day. This time frame was used to determine if the alarm could be heard over everyday living noise. The 10pm-2am time frame was chosen to correspond with the first couple of hours of sleep, generally for adults. Sleep statistics indicate that the deepest period of sleep occurs during the first couple of hours. This 10pm-2am time frame was used to determine if the alarm was loud enough to wake sleepers from their deepest sleep. The 2am-6am time frame was chosen to both see the effect a few hours sleep has on response time latency and catch sleepers influenced by the effects of substances, particularly alcohol. This time period also corresponds to the time where most fire fatalities are occurring.

Volunteer households were told that the alerting device was to be installed for two weeks with the experiment running the entire period. To reduce expectancy of alarms, all events were programmed to occur within ten days of installation, not the expected fourteen. By reducing the time of installation the anticipation of an alarm event was not heightened in the last couple of days of the experiment.

3.5.2 Installation

For minimum protection, it is recommended that domestic smoke alarms be installed between the living areas and the bedrooms. For this experiment it was decided to test the ability of an inexpensive smoke alarm to alert occupants to a fire event when placed in this minimum protection position. The alerting devices were positioned in the hallways, midway between bedrooms. Positioning of the alerting device in a site outside the bedroom enabled investigation of the effects of having the bedroom door open compared with the bedroom door closed. The remote site enabled the whole household to participate in the experiment, widening the scope of the research. With the alerting device in the hallway, the effects of attenuation on the alarm signal could be investigated. The alerting device was attached to the wall in the hallway at arms reach for ease of deactivation.

3.5.3 Audibility Measurement

A sound level meter and peak level meter were used to measure the audibility of the alerting device in each of the bedrooms. The sound meters were positioned at pillow level and the average of five readings were taken from the peak level meter, with the door open then with the door closed. All appliances (TV, stereo, microwave) were switched off to take the readings. The five readings from the peak level meter were averaged and calibrated with the sound level meter to provide a decibel level of the alerting device in each of the bedrooms. The accuracy of the audibility readings is debated in the section 4.3.

Taking audibility measurements with the door open and comparing them with the door closed enables an evaluation of the effect of attenuation on the audibility of the domestic smoke alarm. The readings can also be compared to the design criteria suggesting that a door reduces the sound level of a smoke alarm by 15 dBA.

3.5.4 Details

Details of the members of each household were required for data analysis to determine trends. Personal details of the primary occupant were taken, with details of age, gender and sleeping with the bedroom door open or closed along with audibility readings, taken for additional occupants.

Personal details supplied by the primary occupant included status of home ownership, presence of a fire safety system in the home, identification as a light, medium or heavy sleeper and any acknowledged history of hearing impairment. These details were provided to determine if they are factors which influence response times.

3.5.5 Alarm Action and Answer Machine

On hearing the alerting device alarm, participants were required to switch the alarm off and telephone an answer machine to leave a recorded message. The first person to hear the alarm was required to switch the alarm off to indicate how quickly a person could be notified of a fire event in the home, subsequently notifying others. The primary occupant was not solely responsible for deactivating the alarm as the research was also investigating the ability of people to sleep through an alarm.

A test in human behaviour involved leaving a recorded message on an answer machine immediately after deactivating the alarm. The participant was required to state their name, their assigned code number, the time and estimate the number of people who were woken by or heard the alarm. The message was used to evaluate the ability of people to perform a simple task while in a lethargic sleep state. The answer machine messages were checked for coherence each morning, by the researcher.

3.5.6 Post-Alarm

The day subsequent to the alarm event, a follow up telephone call was made to investigate the details of the alarm event. Questions were asked of the respondent to the alarm. If the alarm was not acknowledged, the reason for this was recorded. Questions asked included:

- The time the alarm activated
- The number of occupants who were in the home and the number who heard or were woken by the alarm
- The age and gender of the occupants who heard or were woken by the alarm
- The time the respondent fell asleep prior to the alarm
- Had the respondent consumed any substances which they consider may have affected their sleep
- Any comments or observations from the alarm event

The answers to the questions are compared, in chapter four, to response time, audibility and waking effectiveness, to establish the effectiveness of the alarm signal at alerting occupants to a fire event.

3.5.7 Data Collection

At the end of the two week period, the alerting devices were collected from the volunteer homes and the response time data down-loaded and recorded. The alerting devices were then reprogrammed and redistributed to the next set of homes. Details of the household, primary occupant and from the post-alarm questionnaires were compared with the response times from the alerting devices to determine the efficiency of the domestic smoke alarm signal.

3.6 Summary

The experimental procedure was devised to collect data which could be used to determine the effectiveness of the inexpensive domestic smoke alarm. The use of a programmable alerting device enabled collection of response times to the alarm signal; the use of questionnaires and audibility readings enabled identification of trends to the data. Trends to the data are identified in chapter four.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

Data collected from the alerting devices installed in volunteer homes and the questionnaires relating to each alarm event, is used to assess whether the domestic smoke alarm signal is effective at alerting occupants to a fire event. The following section looks at what the data from the experiment sets out to prove, what limitations are associated with the data collection and analysis and outlines the specifics of each alarm event. The data is analysed, providing results which can be categorised by looking at response to the alarm, the effects of substances on the response to the alarm and the response of children to the alarm. Some observations from participants in the experiment are provided, with a summary concluding the results.

4.2 Hypothesis

The aim of this research is to analyse the effectiveness of inexpensive domestic smoke alarms as early warning systems by investigation of response times to the alarm signal. Data provided by the experiments is focussed towards proving how effective the smoke alarm signal is. The following hypotheses are contrived from statistics and previous studies of domestic smoke alarms to evaluate, from the experimental data, how effective the alarm signal is.

The hypothesis statements which the analysis of the experimental data sets out to evaluate are:

(1) That domestic smoke alarms currently on the market, if placed in a site outside the bedroom, are loud enough to wake sleepers;

(2) That people influenced by drugs or alcohol will respond slower to the alarm signal than people not under the influence;

(3) Elderly will respond slower to the alarm signal than younger adults;

(4) Children, under ten years old, will be slower to respond to the alarm signal than teenagers and adults;

(5) It is a valid recommendation to put smoke alarms in every room.

4.3 Limitations of Data

Aside from the limitations to the scope of the research, there are limitations and uncertainties associated with the data collection and analysis for the research. The following is a list of the limitations and uncertainties associated with data collection and analysis:

- Audibility – Uncertainties arise with respect to collection and processing of the alerting device audibility measurements. Collection of the data is sensitive to the accuracy of the device, device sensitivity, ambient noise, attenuation and situation of respondent; processing of the data is sensitive to the accuracy of the calibration used to convert millivolt readings of peak sound level to decibels. The measurement of the audibility of the alerting device is accurate to approximately five decibels. The readings are dependent on the resolution of the scale. The sound level meter is sensitive to the pulse signal of the alerting device. The sensitivity of the sound level meter made it necessary to use a peak level meter with the capacity to follow the signal; the peak level audibility can be captured at an instant. Ambient noise is incorporated into the sound level readings of the alerting device An average of five peak level readings are used to minimise the effects of ambient noise on the sound level reading. Measurements of the sound level of the alerting device were taken during the day when the device was installed. Ambient noise varies diurnally causing the alerting device alarm signal to appear louder during the night than during the day. The more significant difference between the sound levels may have an affect on the response times. Attenuation causes variations in the sound level reading of the alerting device. Factors such as having doors open or closed can strongly influence the sound level of the alarm. Situation of the occupant at the time of the alarm influences their ability to hear the alarm. If the occupant is at pillow level in their bedroom, the audibility reading is accurate; if the occupant is anywhere else in the house, it is unknown what the approximate decibel reading of the alerting device alarm is. For cases where the occupants are awake and in their living areas, there are no audibility measurements of the alerting device signal. The calibration of millivolt readings to decibel readings was done using a pure tone in a quiet room. Inaccuracies were involved when doing this calibration.

- Response times – There are uncertainties associated with the response times recorded by the alerting device. Travel distance and travel speed influence response times. Travel distance is dependent on the proximity of the respondent to the alarm; the travel speed is dependent predominantly on the age of the respondent. Neither the additional time for travel distance nor travel speed are subtracted from the response times recorded for each alarm event due to the response times, on average, being less than thirty seconds. Influences, such as a partner waking the alarm respondent, are not factors acknowledged as decreasing the response times.
- Alarm times – Alarm events were distributed one into each of the time frames 6pm-10pm, 10pm-2am and 2am-6am. There was a significant proportion of 'no response' in the 6pm-10pm time frame due to people not being home to respond to the alarm.
- Impairment – Acknowledgment of suffering from hearing impairment is qualitative not quantitative. Four members of the primary group identify as suffering from hearing impairment, but the experiment does not involve measuring the severity of the impairment.
- Substances – Acknowledgment of consuming substances which effect sleep is qualitative not quantitative. The respondents identify having consumed substances, but the experiment does not involve measuring the quantity of substances to correlate with the effect to response times.

- Risk groups – Risk groups are identified from fire incidence and fatality statistics. Comparison between risk groups of response time is limited due to the number of members in each groups being disproportionate. Conclusive trends between the groups cannot be defined.
- Age of participants – There is a bias towards participants aged between twenty and thirty (student risk group). There are not enough teenage age participants in the experiment to determine trends for this group.
- Time to sleep – Respondents to the alarms during sleeping hours were required to identify the time they went to sleep. The time to sleep is only an approximation, subsequently causing the time difference between time to sleep and the alarm time used in the analysis, to be an approximation.
- Fire safety system – There is a bias towards choosing Maori volunteers who do not have a smoke alarm in their home and a bias towards choosing students with a superior knowledge of fire.
- Motivated response – Major influence in the scope of the experiment. Participants were primed to respond to the alarm.

4.4 Alarm Event Details

Forty homes participated in the experiment, volunteering to have an alerting device installed for two weeks; 26 student homes and flats, ten Maori families and four homes owned by elderly volunteered (Figure 4.1). In total, 128 people experienced at least one alarm event. From the 128 people, there were 229 individual exposures to the alarm signal.

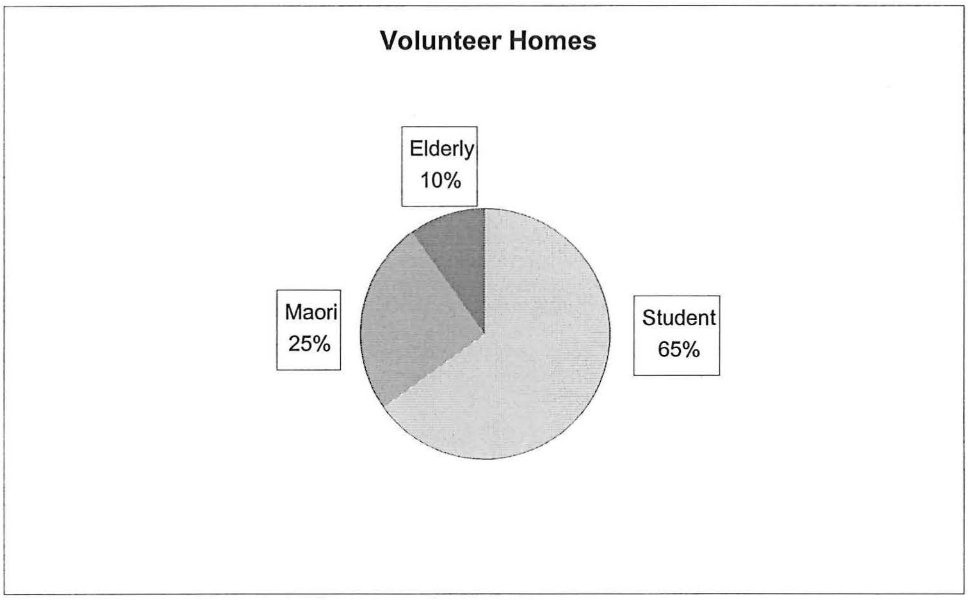


Figure 4.1: Volunteer homes.

The alarm events were distributed into three time frames; 6pm-10pm, 10pm-2am, 2am-6am. Each home was exposed to one alarm from each time frame, totalling three alarms per home. The 25 alerting devices were able to successfully record 119 alarm events (Figure 4.2).

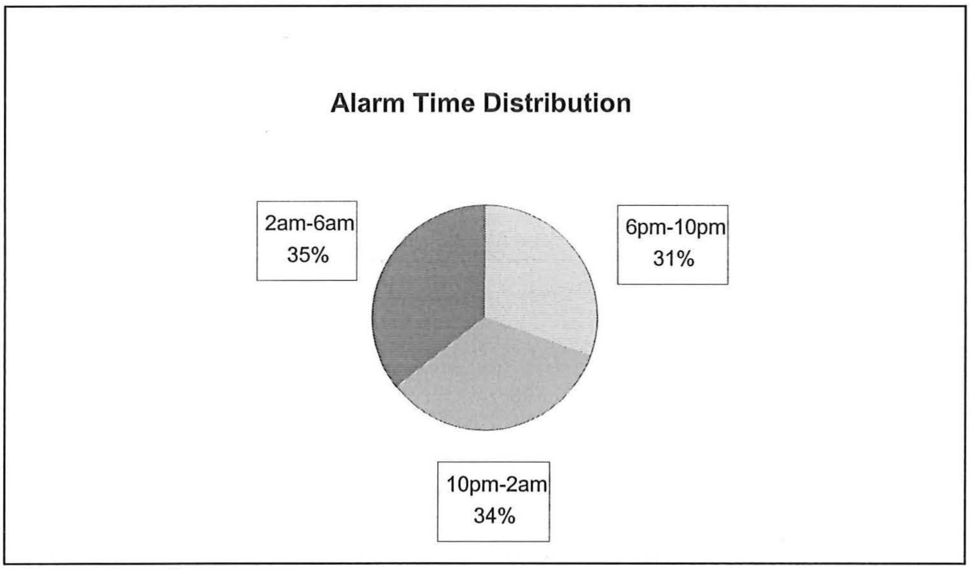


Figure 4.2: Alarm event distribution into time frames.

19 alarm events, out of the 119 total were registered as 'no events' where the alarm was recorded to sound for 255 seconds. Of the 19 'no events', 18 occurred where there was no one home to deactivate the alarm. The one instance of 'no event' where people were home but did not respond to the alarm, the volunteers considered they had consumed substances which had affected their sleep (Figure 4.3).

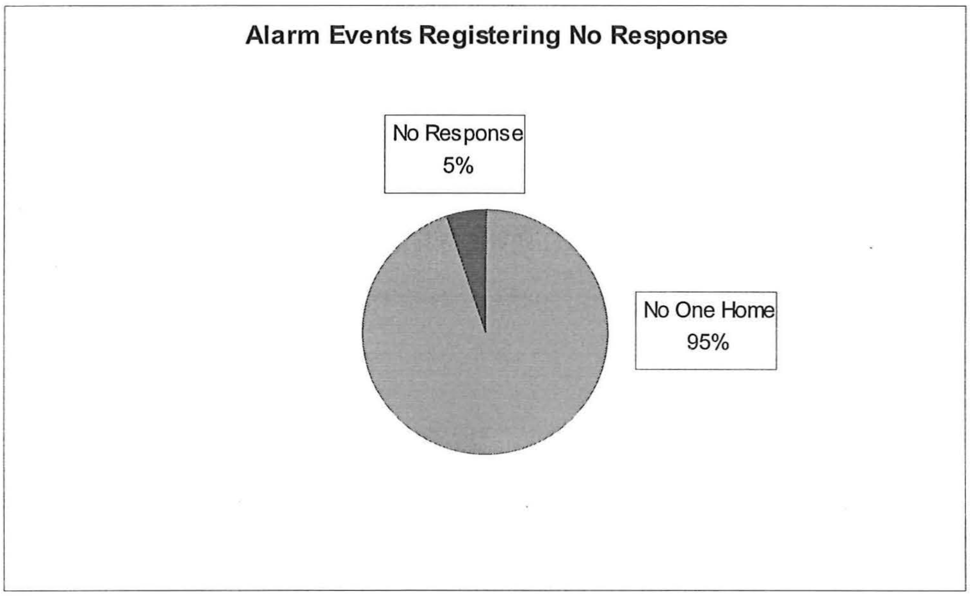


Figure 4.3: Alarm events registering no response.

If the alarm events were cases of real fires, the data shows there would have been 18 house fires with one resulting in a fatality.

The experimental period ran from November 1, 1998 through to December 24, 1998. The 119 alarm events were distributed throughout the week with no day of the week particularly targeted (Figure 4.4).

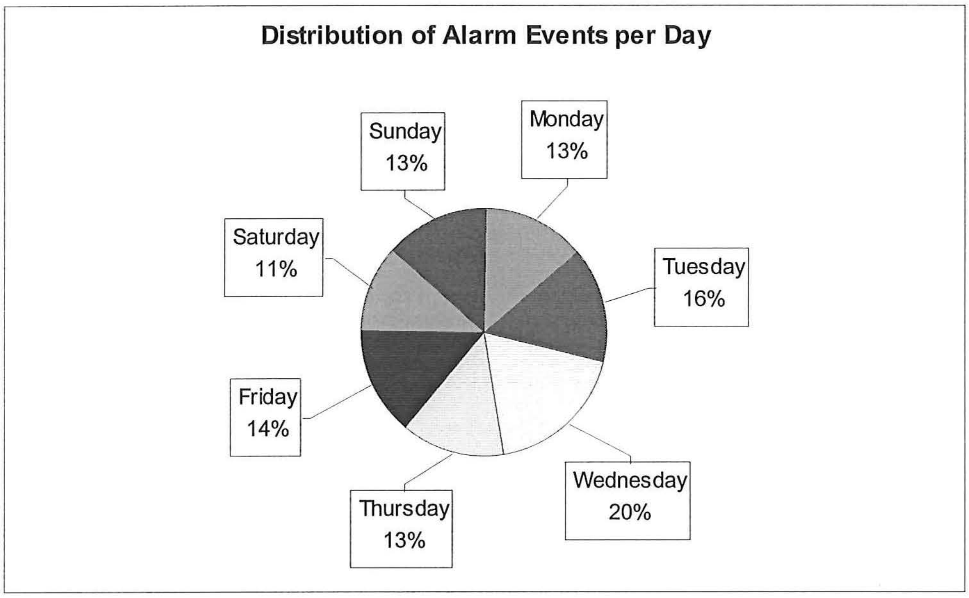


Figure 4.4: Distribution of alarm events per day.

Two special cases of alarm were events investigated. The first case looks particularly at altered response due to consumption of substances which effect sleep; the second looks at children's response to the domestic smoke alarm.

4.5 Response

Response to the alarm is measured as the time between alarm activation and alarm deactivation. Alerting devices were programmed to activate at a specific time, with an internal clock counting the seconds from activation to deactivation. A 'no response' is characterised by a recorded response time of 255 seconds - the time taken for the alerting device to automatically deactivate.

The following looks at patterns to response times as gleaned from data from the experiment. Events of 'no response' are characterised, excluding the occasions where consumption of substances are recognised as affecting respondent's sleep and cases where children under ten years old are involved. The observed effects of audibility, time to sleep and impairment on response times are described and discussed.

4.5.1 Times

The following graph shows the distribution of response times to the alarm signal (Figure 4.5). Values of the distribution exclude 'no response' events and the response times for the case study involving children, but do include response times of respondents impaired by consumption of substances they consider to have effected their sleep.

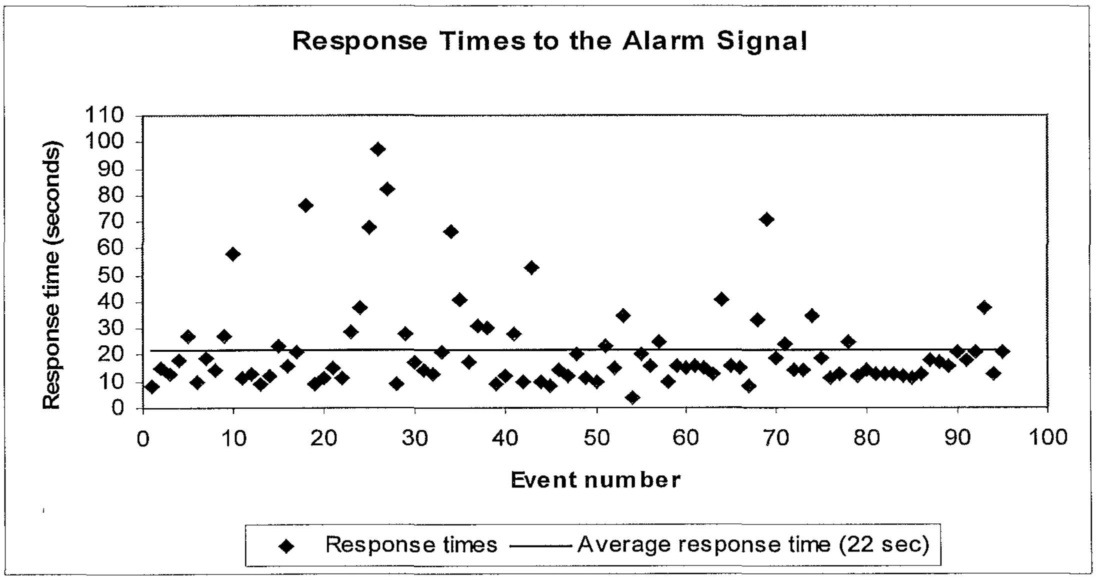


Figure 4.5: Response times to the alarm signal.

A summary of the response times to the alerting device alarm is shown by Table 4.1. Values exclude 'no response' events and response times for the case study of children, but do include response times of respondents impaired by consumption of substances they consider to have effected their sleep.

Table 4.1: Average response times.

Total Group	Average response	22 seconds
Risk Groups	Maori	28 seconds
	Students	19 seconds
	Elderly	26 seconds
Gender	Male	23 seconds
	Female	21 seconds
Time frame	6pm – 10pm	15 seconds
	10pm – 2am	23 seconds
	2am – 6am	26 seconds
Bedroom Door	Open	21 seconds
	Closed	31 seconds

The experiment shows the average response to the alarm signal to be 22 seconds, ranging from a minimum of 4 seconds (recorded from the student group in the 6pm-10pm time frame) to a maximum of 97 seconds (recorded from the elderly group in the 10pm-2am time frame). From the data retrieved, it is shown that the response time to the tested domestic smoke alarm signal located at a site outside the bedroom is, on average, less than 30 seconds.

Having the bedroom door open decreased the response time to the alarm signal by ten seconds. Closing the door was shown to muffle the alarm signal by approximately ten decibels, but results show that the alarm is sufficiently audible with sleeping occupants reliably woken by the alarm while having their bedroom doors closed.

Looking particularly at the identified risk groups, the data shows there to be no significant differences between the average response times of each group. The average response time of students (19 seconds) is faster than the average response time of Maori (28 seconds) and elderly (26 seconds), but this trend cannot be certain due to the disproportionate numbers comprising each group (26 students, 10 Maori, 4 Elderly). Of the elderly participants, there is only one reported case where the participant identified as having a physical disability. The average response time of the elderly participant with the physical disability (82 seconds) is significantly higher than the average response time for the total group (22 seconds). A larger population of elderly and an investigation into the affect of physical disabilities on response time would be essential to enable conclusions to be drawn from the results.

Gender differences appear to have little effect when comparing the response times of females (21 seconds) to males (23 seconds). Females responding to the alarm signal are, on average, slightly faster than males, although this trend is not conclusive as more males than females responded to the alarms.

Results show that the time of night and level of wakefulness does have an affect on response time. The average response time to the alarm sounded between 6pm and 10pm (15 seconds) is significantly faster than the average response times to the alarms sounded between 10pm and 2am (23 seconds), and 2am and 6am (26 seconds). The average response time (15 seconds) recorded for the 6pm to 10pm time period, indicates that the alarm signal is loud enough to be heard above ambient 'living' noise.

Average response times, for the total group, are slowest between 2am and 6am (26 seconds), although more alarm events occurred in this 2am to 6am time frame, perhaps biasing the result. This trend is further investigated in the section comparing response time to time to sleep.

4.5.2 No Response

Of the 229 individual exposures to an alarm event, there were 35 reported cases (15 percent) where the alarm was not heard by participants exposed to the alarm (Figure 4.6).

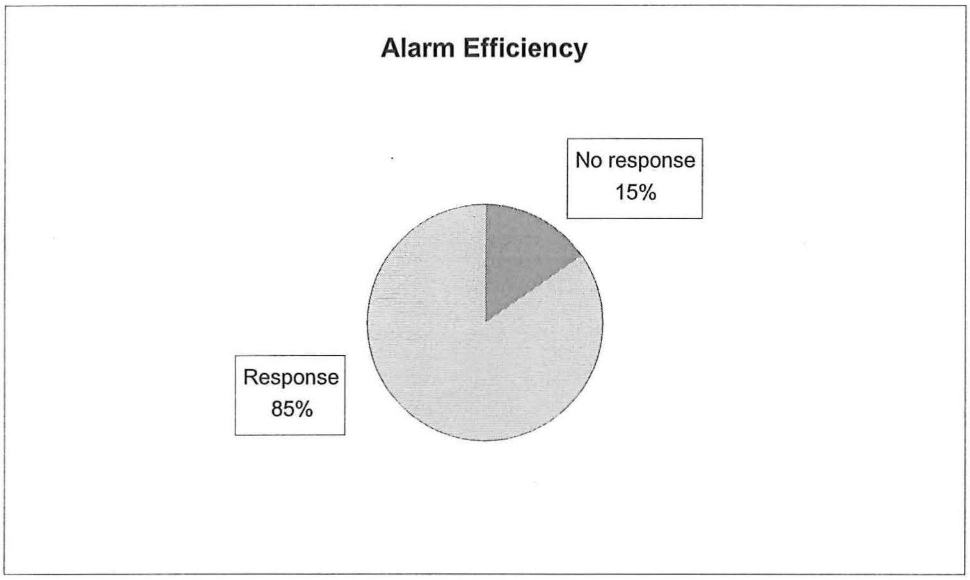


Figure 4.6: Alarm efficiency.

Of the 35 reported cases of no response to the alarm, 9 (26 percent) acknowledged consuming substances which affected their sleep. The effect of substances on response time to the alarm signal is investigated further in section 4.6. There are 26 reported cases (74 percent) of not being woken by the alarm whereby no substances which influence sleep had been consumed. Of the 26 reported cases of not being woken by the alarm, 18 cases (69 percent) involved children under the age of ten. The response of children under the age of ten to the alarm is investigated further in section 4.7. Eight cases, making up three percent of the total individual exposures, are left where participants did not hear the alarm (Figure 4.7).

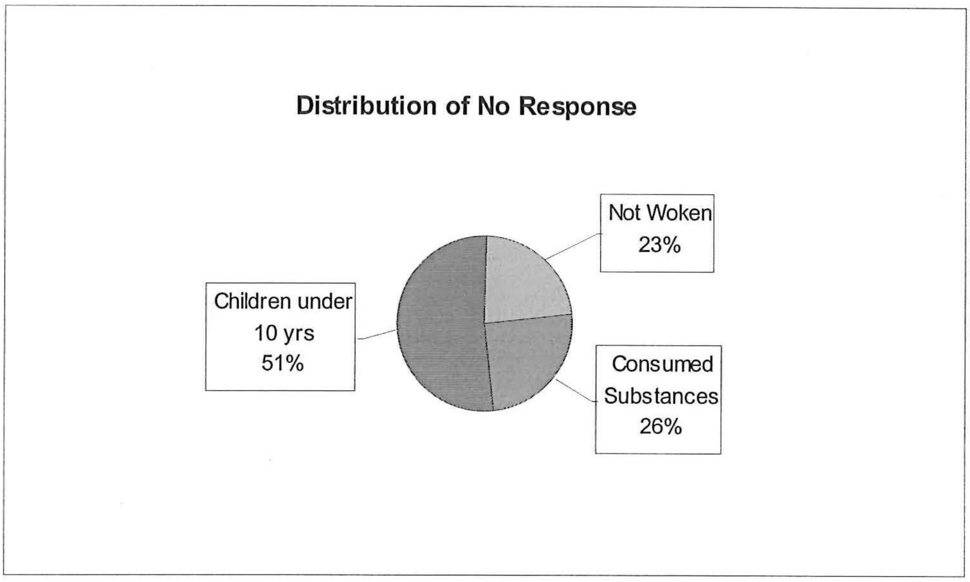


Figure 4.7: Distribution of no response.

The eight cases of no response to the alarm where no sleep-influencing substances had been consumed were all members of the student group. There are no reported cases where a participant, uninfluenced by substances and over ten years old, is repeatedly not woken by the alarm. The eight cases of no response to the alarm are described in Table 4.2.

Table 4.2: Eight cases of no response.

Case	Age	Gender	Audibility of alarm	Door	Time of alarm activation	Comment on no response
1	25	F	71 dBA	Closed	2:11 am	Slept
2	17	F	71 dBA	Closed	1:43 am	Slept
3	34	F	66 dBA	Closed	4:59 am	Slept
4	23	F	65 dBA	Closed	12:11 am	Slept
5	41	M	65 dBA	Closed	3:43 am	Slept
6	21	F	62 dBA	Closed	5:59 am	Slept
7	28	M	62 dBA	Closed	5:59 am	Slept
8	24	F	66 dBA	Closed	12:32 am	Slept

Audibility of the alarm appears not to be an influential factor contributing to the 'no response' as the audibility readings for the eight cases are not significantly different from the average audibility for the total group (75 dBA, door open; 67 dBA door closed). The alarms all sound significantly above ambient noise levels appropriate for night time (estimated to be 20 dBA). The age of the participants not woken by the alarm relates to the deep sleep patterns characteristic of 20–26 year olds. Sleep statistics record that the 20–26 year old age group experience a high amount of deep sleep, requiring a strong stimulus to awaken. The results from this study show that it is this 20–26 year old age group which are not being woken by the alarm signal, but more investigation into the validity of this conclusion is required.

The reported cases of not being woken by the alarm appear to be isolated cases where people report being particularly tired or believe to have been in a particularly deep sleep. The results do not show that it is heavy sleepers who are particularly susceptible to sleeping through an alarm as all the identified heavy sleepers from the primary group were successfully woken by the alarms.

4.5.3 Audibility

Audibility readings of the alerting device alarm were taken in each bedroom with the door open then again with the door closed. Care was taken to place the alarm in the hallway, midway between bedrooms, to ensure all occupants could receive a signal. The average audibility of the alarm with the bedroom door open was found to be 75 decibels (61 dBA minimum, 93 dBA maximum); the average audibility of the alarm with the bedroom door closed was found to be 67 decibels (57 dBA minimum, 75 dBA maximum) (Table 4.3). (Average values for audibility exclude those used for the case study – section 4.7.1)

Table 4.3: Average audibility readings.

Door	Average Audibility	Maximum	Minimum
Open	75 dBA	93 dBA	61 dBA
Closed	67 dBA	75 dBA	57 dBA

The values from the experiment for audibility show that doors dampen the sound of the alarm by an average of nine decibels. Design calculations for attenuation of alarm state that a door will muffle the sound of an alarm, on average, by 15 dBA (Schifility et al, 1995). The data selection indicates that the value used for calculation is conservative. Consideration should be made to the uncertainties associated with the alarm. The uncertainties associated with the measurement of audibility of alarm events are documented in the section 4.3. Sounding systems are designed to achieve between 65 dBA and 75 dBA in rooms of sleeping accommodation (Schifility et al, 1995). The results show that the inexpensive smoke alarm signal is reaching sound levels, on average, within those required for design calculations.

The data shows no trend to prove that there is a minimum level of audibility which the alarm cannot be heard from. Section 4.5.2 shows the effect audibility of the alarm has on the events of no response to the smoke alarm.

An assumption would be that the louder and more salient the alarm, the quicker the alarm would wake and the faster the response time would be. Results would show a negative correlation between response time and audibility; the louder the alarm, the quicker the response. Results suggest that increased audibility has a minor effect on decreasing the response times to being woken by the alarm; the relationship is highlighted by the trendline of the graph (Figure 4.8).

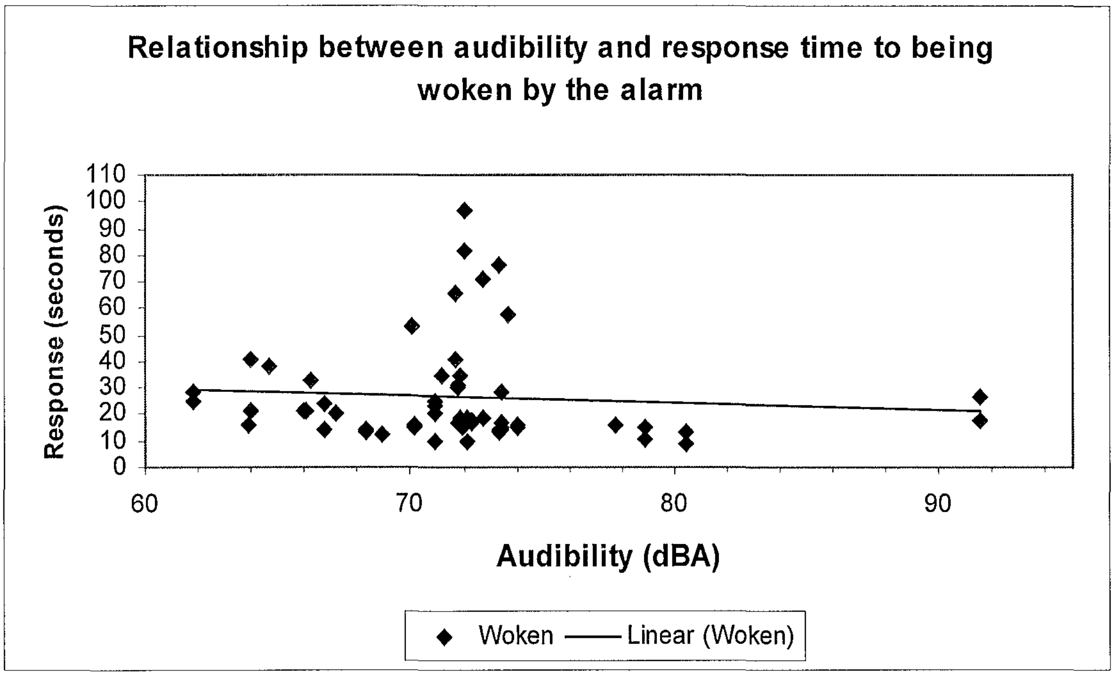


Figure 4.8: Relationship between audibility and response time to being woken by the alarm.

The results show a slight trend towards increased audibility decreasing the response time to the alarm signal but more investigation into this trend is required as the number of events where the audibility of the alarm is above 75dBA, is limited.

4.5.4 Time to sleep

The results described in section 4.5.1 show that average response time to the alarm sounded between 6pm and 10pm (15 seconds) is significantly faster than the average response times to the alarms sounded between 10pm and 2am (23 seconds), and between 2am and 6am (26 seconds). Studies investigating patterns to sleep indicate that the stage of deepest sleep occurs within the first couple of hours of sleep. Data shows that the majority of people participating in the experiment go to bed before midnight, indicating that the first couple of hours of sleep occurs within the 10pm to 2am time period. The sleep data implies that the response time to the alarm signal would be slower in the 10pm to 2am time period, where respondents are in their deepest stage of sleep, than the 2am to 6am time period, where respondents have had more sleep. The effects the amount of sleep prior to the alarm on the response time are investigated to see if the amount of sleep has an effect on the ability to be woken by a domestic smoke alarm.

To investigate the effects on response times caused by more sleep prior to the alarm, data was looked at whereby the same participant had been woken by and responded to the alarm twice; once between 10pm and 2am and once between 2am and 6am. The comparison of the two sleeps is summarised in Table 4.4.

Of seventeen the cases where one participant responded to both alarms, five were Maori, four were elderly and eight were students. Four females responded twice and thirteen males responded twice to the alarm signal.

To compare the effects of more sleep on the response time to the alarm signal, the response time of the alarm event between 2am and 6am was subtracted from the response time of the alarm event between 10pm and 2am; a positive difference implied that the response in the second time frame was faster than the response in the first. The response was then compared to the difference in the amount of sleep had prior to the alarm event. The difference in the amount of sleep was calculated by subtracting the amount of sleep had prior to alarm event between 10pm and 2am from the amount of sleep had prior to the alarm event between 2am and 4am; a positive difference implying more sleep was had prior to the alarm event between 2am and 4am.

Results show that there were four cases where the response to the alarm signal was slower between 2am and 6am than it was between 10pm and 2am. In three of the four cases, more sleep was had prior to the 2am-6am alarm. In one case of the four, more sleep had been had prior to the 10pm-2am alarm than prior to the 2am-6am alarm, proving the response to the alarm to be faster with more sleep. Thirteen cases of the response to the alarm being faster in the 2am-6am time period where the occupants had had more sleep prior to the alarm were recorded. Of the fifteen cases, six appear not significant as the difference between the response times is less than two seconds.

The results from the experiment suggest that the response to the alarm signal is quicker the more sleep is had prior to the alarm (Table 4.4). More investigation into this finding is required due to the number of cases where the difference between the two response times is not significant. Uncertainties arise in evaluating the amount of time the respondents slept prior to the alarm; the time the respondent fell asleep is only an approximation. Monitoring of sleep patterns would be required to report accurate times to sleep.

Table 4.4: The affect more sleep prior to the alarm has on response time to the alarm signal.

Case	Alarm time	Response (seconds)	Amount of sleep prior to the alarm	Response Difference	Comments
1	22:23	18	0:53	9 sec	Faster with less sleep
	5:43	27	6:43		
2	1:52	23	1:22	7 sec	Faster with more sleep
	5:23	16	5:23		
3	1:43	21	2:13	55 sec	Faster with less sleep
	4:59	76	5:59		
4	0:59	11	2:59	4 sec	Faster with less sleep
	3:03	15	5:03		
5	0:03	97	1:03	15 sec	Faster with more sleep
	4:03	82	5:03		
6	0:32	28	2:32	11 sec	Faster with more sleep
	3:23	17	5:23		
7	21:43	14	0:43	1 sec	Faster with more sleep
	23:23	13	2:08		
8	23:32	66	1:32	25 sec	Faster with more sleep
	4:43	41	6:43		
9	23:11	31	1:41	1 sec	Faster with more sleep
	4:52	30	7:22		
10	5:59	16	5:29	9 sec	Faster with more sleep
	5:30	25	1:00		
11	1:11	16	1:41	1 sec	Faster with more sleep
	5:52	15	7:22		
12	1:43	16	3:43	1 sec	Faster with more sleep
	4:59	15	5:59		
13	0:52	71	0:52	52 sec	Faster with more sleep
	3:11	19	3:41		
14	0:32	24	1:02	10 sec	Faster with more sleep
	3:23	14	4:53		
15	0:43	35	3:13	16 sec	Faster with more sleep
	3:32	19	3:32		
16	0:03	14	0:48	1 sec	Faster with more sleep
	4:03	13	4:48		
17	23:23	18	0:23	1 sec	Faster with more sleep
	4:32	17	6:02		

4.5.5 Impairment

Studies suggest a sound pressure level between 55 and 70 dBA will awaken a college-aged person with normal hearing (Schifility et al, 1995). There are three members of the primary group who identify as suffering from a form of hearing impairment, subsequently perceiving the alarm signal at a different sound level from that measured (Table 4.5).

Table 4.5: Details of hearing impaired.

Age	Gender	Alarm Time	Response	Audibility
25	Male	19:03	13	92 dBA
		22:23	18	
		5:43	27	
76	Male	21:11	68	72 dBA
		0:03	97	
		4:03	82	
73	Male	21:43	14	73 dBA
		23:23	13	

Results from the study show that the alarm signal was loud enough to awaken the sleeping subjects who identified as suffering from hearing impairment. No participants who identified as suffering from a form of hearing impairment slept through an alarm event. Ranges of the audibility of the alarm are, for the hearing impaired, above the suggested sound pressure levels of between 55 and 70 dBA found effective at awakening people with normal hearing (Schifility et al, 1995).

The average response time of a person with a hearing impairment is 41 seconds. This response time is significantly different from that of the total population (22 seconds). Reasons for this significant difference arise from the small sample size of hearing impaired (2.3 percent of the total population). The individual cases where response times are significantly above the average response time of the total population, correspond to a 76 year old male who suffers also from a physical disability. The average of the remaining response times (17 seconds) is not significantly different from the average response time of the total population (22 seconds).

Uncertainties with this result arise from the qualitative measurement of the hearing impairment; the degree to which the participant's hearing was affected is not measured. The results suggest that the alarm is loud enough to awaken people who suffer from hearing impairment, but more investigation is required. Coincidentally, the participants who suffered from hearing impairment slept with their bedroom doors open; the audibility of the alarm is greater with the bedroom door open. Research into the effects of closing the door, hence lowering the audibility of the alarm, is required.

4.6 Substances

Of the 128 people participating in the experiment, 13 acknowledged consuming substances, prior to being woken by an alarm, which they consider to have affected their sleep. Each of the 13 participants were members of the student group and influenced by sleep altering substances once out of their maximum of three exposures to the alarm; there are no repetitive cases. Of the 13 cases where sleep altering substances were consumed, nine people (69 percent) did not respond to the alarm before it was deactivated by another occupant (Figure 4.9).

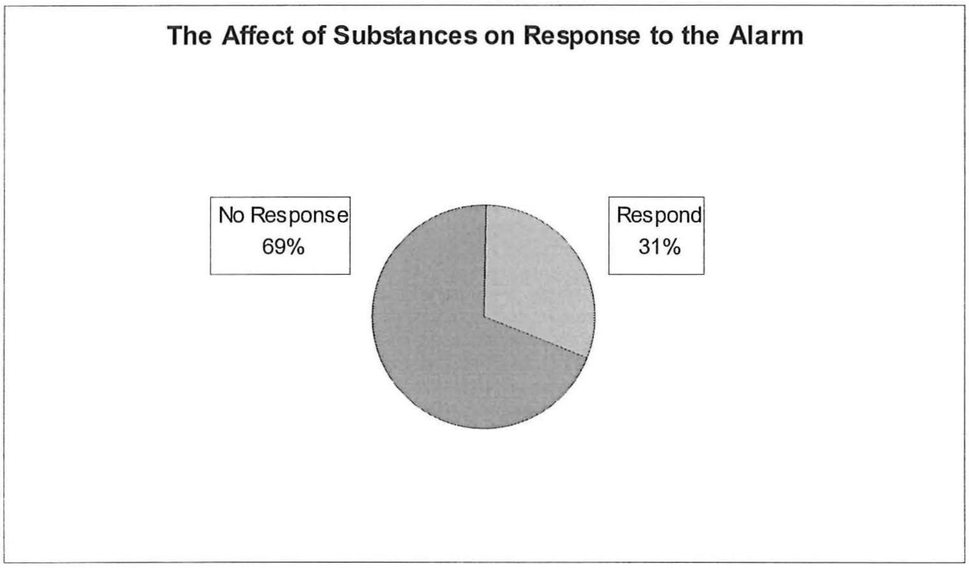


Figure 4.9: The affect of substances on response to the alarm signal.

There are two cases where the occupants who deactivated the alarm acknowledge being influenced by substances which effected their sleep. The response times for these cases were 25 seconds and 53 seconds. 25 seconds is not significantly different from the average response time of the total group of 22 seconds; the response time 53 seconds is significantly different from the average response time of the total group.

Alcohol and marijuana were identified, by willing participants, as substances considered to have effected sleep prior to the alarm.

4.6.1 No Response

The high proportion of cases (69 percent) who consumed sleep altering substances prior to the alarm and were not woken by the alarm, indicates that substances do have a detrimental effect on response to a smoke alarm. Studies show that people under the influence of substances spend longer in the deep sleep state during the initial stages of their sleep as compared to people whose sleep is not influenced by substances. The results suggest that a stronger stimulus is required to awaken people from sleep influenced by sleep-altering substances such as alcohol and marijuana.

Of the nine cases of no response, there is only one instance where fatalities would have occurred had the alerting device alarm been a genuine fire cue. This case involved a couple, living alone, both having consumed large quantities of alcohol; neither heard the alarm. This one instance makes up approximately one percent of the sample population. Of the other instances where sleep-altering substances had been consumed, at least one member of the household had heard the alarm enabling, in a genuine fire situation, others to be alerted. The data suggests recommendations to make the fire alarm signal more salient would only be necessary for approximately one percent of the population.

4.6.2 Case Study

Background literature suggests that people's response to an alarm signal will be slower if their senses are dulled due to the consumption of alcohol. To investigate this fact, an alerting device was installed in a student flat and programmed to activate at 5:30am, the morning after a function where large quantities of alcohol had been consumed. The occupants had volunteered to participate in the two week study and were aware the alarm was installed but naive of when the alarm was set to activate. Four people lived at the flat with five guests staying the night of the function; some of the guests were asleep in the living room at the time of the alarm. The age of the occupants ranged from 21 to 31 years. The occupants were asleep for approximately one hour before the alarm activated.

Of the nine people asleep in the flat at the time of the alarm, three people (one third) were woken by the alarm; the remaining six occupants (two thirds) did not hear the alarm. Some guests sleeping in the unfamiliar surroundings of the living room with the alarm audibility measuring 68 dBA, were not woken by the alarm. The alarm was responded to in 25 seconds, a response not significantly different from that of the average for the total group (22 seconds) and the average for the student group (19 seconds).

Results from the case study suggest sleeping people influenced by substances which they consider to have affected their sleep, predominantly alcohol, are less likely to be woken by the smoke alarm signal. This conclusion is reinforced by other cases from the research where substances were consumed and people were slower than average to respond to the alarm, or did not wake up.

4.7 Children

Studies suggest that children under the age of ten are not reliably woken by the smoke alarm signal. Children spend longer than adults in periods of deep sleep, requiring a strong stimulus to be woken. The following section looks at the events of the experiment where children were exposed to the smoke alarm signal.

4.7.1 No Response

There were eight under ten year old children involved in the experiment, each being exposed to at least one alarm event. The children's age ranged from one to nine years old, with four females and four males. The average audibility of the alarm signal in the children's bedroom is 78 dBA with the door open and 66 dBA with the door closed, compared to 75 dBA (door open) and 67 dBA (door closed) for the total group. The audibility readings of the alarm in the children's bedrooms are not significantly different from the audibility of the signals waking adult participants (Table 4.6).

Table 4.6: Details of the response of children to the alarm signal.

Case	Alarm Time	Age	Gender	Door	Audibility	Woken
1	1:32	6	M	Open	76 dBA	NO
		5	F	Open	76 dBA	NO
	5:59	6	M	Open	76 dBA	NO
		5	F	Open	76 dBA	NO
2	22:23	3	M	Open	79 dBA	NO
	5:43	3	M	Open	79 dBA	NO
3	22:03	5	M	Open	74 dBA	NO
	2:23	5	M	Open	74 dBA	NO
4	1:23	3	M	Closed	65 dBA	NO
		1	F	Closed	55 dBA	NO
	5:32	3	M	Closed	65 dBA	NO
		1	F	Closed	55 dBA	NO
5	0:59	9	F	Open	81 dBA	YES
		6	F	Open	81 dBA	NO
	3:03	9	F	Open	81 dBA	YES
		6	F	Open	81 dBA	NO

Of the eight under ten year old children, one child (aged nine) was reliably woken by the alarm, seven (87.5%) did not respond when exposed to two alarms (Figure 4.10).

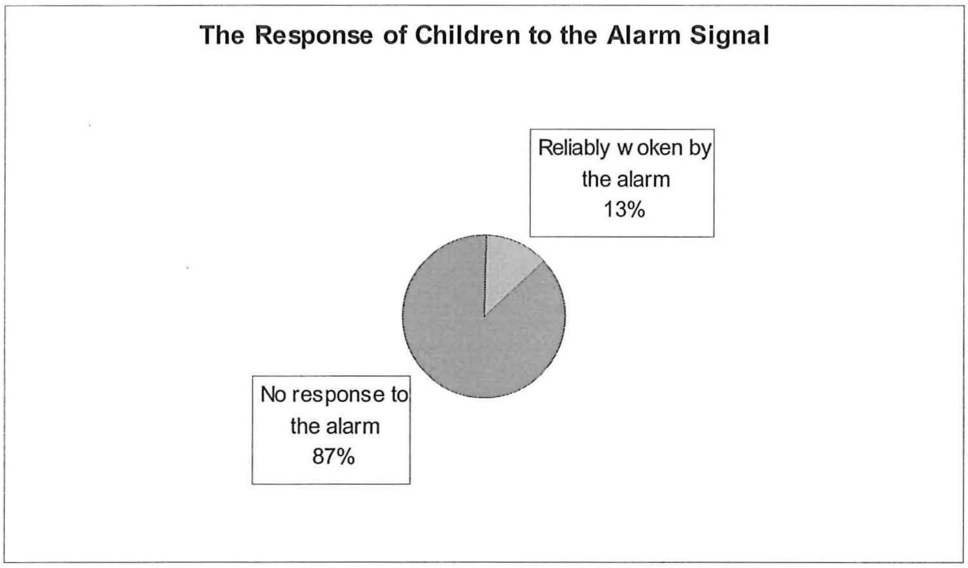


Figure 4:10: The response of children to the alarm signal.

The results from the investigation show that the signal from the domestic smoke alarm does not reliably wake children aged under ten years old and children awake at the time of the alarm are likely to hear the alarm and respond to it.

4.7.2 Case Study

A three year old male child was exposed to a total of five alarms between the hours of 6am and 6pm. The child was familiar with the alarm signal but naive to the possibility of the alarm activating; there was no motivated response. Two positions of an alerting device were investigated in order to gauge the response of children to the smoke alarm signal:

(1) In the hallway outside the bedroom,

(2) In the bedroom.

The audibility of the alarm in the child's room with the alarm positioned in the hallway was 65 dBA; the audibility of the alarm at pillow level was 91 dBA with the alarm positioned in the child's bedroom. The audibility of the alarm, positioned in the hallway, was not significantly different from the average audibility used to alert adults with their bedroom doors closed (67 dBA). The audibility of the alarm positioned in the bedroom is louder than the average audibility used to alert adults with the bedroom door opened (75 dBA). It was the responsibility of the parents to deactivate the alarm when they were alerted to it.

The alarm events and the child's response are described in the following table (Table 4.7).

Table 4.7: Case study results – child's response.

Alarm Position	Age	Gender	Alarm Time	Audibility	Response time – adult	Response of child
Hallway	3	Male	1:23	65 dBA	16 seconds	SLEPT
			5:32	65 dBA	15 seconds	SLEPT
Bedroom	3	Male	23:15	91 dBA	22 seconds	SLEPT
			2:20	91 dBA	215 seconds	SLEPT
			5:30	91 dBA	20 seconds	SLEPT

The results show that the child was not woken by the alarm with it neither positioned in the bedroom nor in the hallway.

Limitations of the case study into the response of children to the alarm include:

(1) The alarm was deactivated within an adult's response time, with the alarm sounding for an average of 28 seconds. The child was not required to deactivate the alarm himself. No children aged under ten years were required to deactivate the alarm as part of the experiment. Further investigation into the effects of extending the alarm time are required. It was not determined if the under ten aged children would have eventually been woken by the alarm if their exposure time to the alarm signal were increased.

(2) A three year old male was the only child used to compare the effects of position of alarm on the ability for it to awaken under ten year old children. A larger sample size of children would be required in order to form conclusions from the experiment.

4.8 Comments

Discussion with participants involved in the response to the alerting device experiment resulted in the following comments and observations:

- Intoxicated people involved in the case study commented that they would not have been woken by the alarm if it had sounded for longer than the twenty-five seconds.

- One mother tried to wake her six year old daughter after a 3:03am alarm had been deactivated in 15 seconds to determine, as the child did not respond to the alarm, how much noise would be required to wake the girl. The child's bed required shaking before she was woken.

- A 76 year old man was disorientated when woken by a 4:43am alarm and fell over when moving to deactivate the alarm; he was not injured.

- A 72 year old lady comments she thought an 11:23pm alarm, activating two hours after she went to sleep, was the timer from her bread-maker and thought the alarm was particularly loud that morning. Although she was familiar with the alarm signal, the alarm was still identified as the more familiar cue of her bread-maker which activated every morning. The lady's 73 year old husband deactivated the alarm in 13 seconds.

4.9 Summary

The investigated smoke alarm signal is loud enough to wake most occupants. The exception to the rule are children under the age of ten and occupants whose sleep is influenced by substances. Having the bedroom door open or closed has no effect on the ability of the alarm to awaken sleeping occupants. From the data gathered, the alarm was found to be 85% reliable at alerting occupants to a fire event, with only 35 incidents out of 229 where a participant did not hear the alarm.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The aim of this research was to analyse the effectiveness of inexpensive domestic smoke alarms as early warning systems, by investigation of response times to the alarm signal. Research was done by using a computerised alerting device, programmed to activate in homes between 6am and 6pm, to test the response time to a smoke alarm signal. Data collected from the alerting devices and questionnaires relating to the alarm events were used to assess whether the domestic smoke alarm signal investigated is effective at alerting occupants to a fire event.

5.2 Proof of Hypothesis

Data provided by the experiments was focussed towards evaluating the effectiveness of the smoke alarm signal. Conclusions from the data analysis evaluate the research hypotheses and rate the effectiveness of the domestic smoke alarm signal.

Each hypothesis was tested by investigation of data collected from the experiment and the following conclusions were made.

- Hypothesis One - That domestic smoke alarms currently on the market, if placed in a site outside the bedroom, are loud enough to wake sleepers.

Domestic smoke alarms currently on the market, if placed in a site outside the bedroom, are loud enough to wake sleepers. Proof of this conclusion arises from the investigation of a ‘pulsing’ alarm produced by an inexpensive stand-alone domestic smoke alarm. When placed in the hallway adjoining bedrooms, the alarm signal recorded an average of 75 dBA with the bedroom door open and 67 dBA with the bedroom door closed. At night, these sound pressure levels are more than the 15 dBA above ambient noise advised as the sound level most effective at waking occupants from sleep.

The alarm signal used was found to be 85% effective with only 35 out of a possible 229 alarm events gone undetected. Of the 35 events, 9 (26%) involved participants consuming substances which they consider to have affected their sleep prior to the alarm event, 18 (51%) involved children under the age of ten and 8 (23%) were genuine cases where adults were not woken by the alarm. Removing the lack of response to the alarm caused by participants consuming substances which they consider to have effected their sleep, the reliability of the alarm increases to 89%. There were no reported cases of the alarm not being heard by occupants who were awake at the time of the alarm.

The average response of the occupants to the alarm signal was found to be 22 seconds, with response to the alarm being quicker when occupants were awake (15 seconds) compared to response when the occupants had to be woken (10pm-2am - 23 seconds and 2am-6am – 26 seconds). Increased audibility had no effect on decreasing the response time to the alarm signal.

- Hypothesis Two - That people influenced by drugs or alcohol will respond slower to the alarm signal than people not under the influence.

From the data gathered, people influenced by drugs or alcohol will respond slower to the alarm signal than people not under the influence. It was found that the intoxicated do not reliably wake to the sound of the domestic smoke alarm. Of the 13 people who identified as consuming substances which they consider to have effected their sleep, 9 (69%) were not woken by the alarm. Response times to the alarm recorded by two people who were intoxicated at the time of the alarm are not significantly slower than the average response time to the alarm signal, but conclusions are limited due to the small sample size.

- Hypothesis Three - Elderly will respond slower to the alarm signal than younger adults.

Results from the experiment were inconclusive in determining if the elderly respond slower to the alarm signal than younger adults. The sample size of four elderly limited the ability to draw conclusions from the results. It was found that the alarm was successful in alerting the hearing impaired, with four participants recognised as suffering from hearing impairment, reliably being woken by the alarm. Recognition of hearing impairment was qualitative, with no measurement as to the severity of the impairment.

- Hypothesis Four - Children, under ten years old, will be slower to respond to the alarm signal than teenagers and adults.

Children, under ten years old, will be slower to respond to the alarm signal than teenagers and adults. Results from the experiment find that children, under the age of ten, are not reliably woken by the alarm signal. Eight out of nine children (89%) aged under ten involved in the experiment, did not wake to one or more exposure to the alarm signal. The audibility of the alarms installed in children's bedrooms was not significantly different from the audibility of the alarms in bedrooms of adults. The alarms which children were exposed to were generally terminated in less than 30 seconds. Limitations to these findings result from the exposure time to the alarm. Questions arise as to if under ten year old children will respond to the alarm if the alarm is left to activate longer than 30 seconds.

- Hypothesis Five - It is a valid recommendation to put smoke alarms in every room.

It is a valid recommendation to put smoke alarms in every room. Literature suggests that positioning smoke alarms in every room adds an extra two and one half minutes to the time available for occupants to escape a burning building. With general trends of literature suggesting the safety period before a fire becomes life threatening is two and one half minutes, the extra warning time provided by the domestic smoke alarm has the potential to be life saving.

Results from the experiment show that the domestic smoke alarm placed in a hallway site outside the bedroom is effective at alerting occupants to a fire event. The alarms were proven to be 85% efficient.

5.3 Recommendations

Research into the effectiveness of inexpensive domestic smoke alarms have found that they are effective at alerting occupants to a fire event. The alarm was found to reliably alert 85% of the population. Of the 15% not woken by the alarm, 4% involved participants who acknowledged consuming substances which they consider to have effected their sleep prior to the alarm. A registered one alarm out of a total of 101 (less than 1%) would have resulted in a fatality. Of the additional 100 alarms, at least one member of the household was alerted to the event

The lack of response of children to the domestic smoke alarm highlights an important aspect with respect to the positioning of the alarms. The alarms located in the hallways adjacent to bedrooms were loud enough to be heard by adults, but the children were oblivious to the alarm. For the alarms to be effective as early warning systems, research recommends that they be interconnected. Interconnectedness would assure that if a fire occurred in a room remote from the area in which the adult is living, the alarm can be heard.

Sleeping with the bedroom door closed has no influence on the ability of an alarm positioned in a site outside the bedroom alarm to alert occupants to a fire event. The alarm signal registered considerably above ambient night and day living noise and was reliable in both awakening and alerting occupants.

In summary, the inexpensive smoke alarm is effective at alerting occupants to a fire event. The alarm was found to be 85% reliable, with children aged under ten years and adults influenced by alcohol and sleep altering substances, identified as not reliably being woken by the alarm. It is recommended that domestic smoke alarms be interconnected to ensure all members of the home hear the alarm. Alarms positioned outside the bedroom are able to alert sleeping occupants but it is recommended that adults who regularly experience sleep influenced by alcohol, install smoke alarms in bedrooms.

5.4 Future Study

Investigation into the ability of inexpensive domestic smoke alarms to provide early warning to a fire found the alarms to be 86% reliable at awakening occupants; 33 incidents out of a total of 226 (15%) occurred where the alarm failed to alert. Removing respondents to the alarm who had consumed substances which they consider to have effected their sleep, the reliability of the alarm increases to 89%.

To decrease the 11% - 15% of the population not reliably woken by the alarm signal, research is required to identify how these risk groups can be minimised. The following are recommendations of areas, identified from this research, which have potential for increasing the reliability of the domestic smoke alarm:

(1) Alarm signal – The research investigated the signal of only one brand of inexpensive domestic smoke alarm. Variations in the alarm signal could be studied to find the optimum alarm signal for alerting occupants to a fire event.

(2) Children – Research found that children under the age of ten are not reliably woken by the signal of an inexpensive domestic smoke alarm. Research into increasing the ability of the domestic smoke alarm to awake children is required.

(3) Alcohol – Research found that adults who had consumed substances which they consider to have effected their sleep, for example alcohol, are not reliably woken by the signal of the inexpensive smoke alarm. Research into investigating how the smoke alarm signal can be made more salient to target the intoxicated, is required.

There is a lot of scope for future research into the effectiveness of domestic smoke alarms. Domestic smoke alarms currently on the market are reliable, but research is required into ways of increasing their reliability, particularly in the areas of the alarm signal, the ability to wake children and the effects of alcohol on response.

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