Drivers’ Ability to Localize Auditory and Haptic Alarms in Terms of Speed and Accuracy

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Thesis submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science in

Industrial and Systems Engineering

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June 29, 2004 Blacksburg, Virginia

Key words: Auditory Alarm, Sound Localization, Spatial Audio Display, Haptic Display, Collision Avoidance System, Collision Avoidance Alarm, Signal Detection Theory, Auditory Alarm Design, Masking, Choice Response Time, Accuracy, Front/Back Confusion, Localization Error, Directional Cueing, Driver Safety
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(Abstract)

This study investigated automobile drivers’ ability to localize auditory and haptic (touch) alarms in terms of speed and accuracy. Thirty-two subjects balanced across age (20-30 years old and 60-70 years old) and gender participated. Subjects were screened for minimum hearing of 40 dB for 500 Hz through 4000 Hz auditory tones, and maximum bilateral hearing differences of 10 dB. The experiment consisted of subjects identifying the target location of an alarm while driving a 2001 Buick LeSabre at 55 mph in light traffic. Four alarm modes were tested: 1) an auditory broadband alarm, 2) a haptic seat, 3) a combination of the haptic and the auditory alarm modes, and 4) a combination of the haptic alarm mode with a non-directional auditory alarm played from the front speakers of the vehicle. The alarms were evoked from eight target locations: the front-left, front, front-right, right, back-right, back, back-left, and left. The target locations of the auditory alarm mode existed around the interior of the car cabin using the vehicle’s stock sound system speakers. The haptic alarm target locations existed in the bottom of the driver seat using an eight-by-eight grid of actuators. The experimenter evoked the alarms while subjects drove along a two-lane highway. The alarms were not associated with any actual collision threat. Subjects were instructed to quickly identify the location of the alarm by calling it out, while being as correct as possible. Their choice response time and target location selection was recorded. The alarms were presented approximately every minute during fifteen-minute intervals over the duration of two and a half hours. Subjects completed questionnaires regarding their preference to the alarm modes. Under the conditions investigated, subjects localized the haptic alarm mode faster and more accurately than the auditory alarm mode. Subjects performed equally well with the haptic alarm mode and the two auditory and haptic combination alarm modes in terms of speed and accuracy in identifying their location. Subjects’ did express a preference for the addition of the auditory component to the haptic alarm mode, perhaps owing to a heightened sense of urgency. However, subjects preferred the haptic alarm mode on its own in response to hypothetical false alarm questions, perhaps because it was less annoying. Alarm mode discriminability was believed to affect localization accuracy and response time owing to its effect on the likelihood of correctly identifying a target location and the attention resources required to differentiate adjacent target locations.
Acknowledgements

This research was supported in part by a contract from the General Motors Corporation for the Virginia Tech Transportation Institute. The author gratefully acknowledges Dr. Raymond J. Kiefer, from the General Motors Structure and Safety Integration Center and the Crash Avoidance Metrics Partnership, for allowing this research to be carried out as a thesis. Dr. Kiefer’s sage guidance in serving on my committee proved to be invaluable. I owe a great amount to Dr. Jon Hankey and Shane McLaughlin, from the Virginia Tech Transportation Institute. Their instruction brought me to a higher level of academic maturity. I would like to thank the members of my committee, Dr. Brian Kleiner, Dr. Kari Babski-Reeves, and Dr. Suzie Lee for taking me on as a student and challenging me to always think one step further. I would also like to thank the following individuals: Donald Grimm from GM for developing the experiment’s test software, Randy Stanley from Head Acoustics for explaining the auditory display equipment as well as the behavior of sound inside a vehicle cabin, and Julie Cook from VTTI. This work is dedicated to my parents, Stephen and Monique, who taught me that education brings fulfillment, and that any situation can be managed through formulation of a plan.
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Introduction

The convenience of automotive transportation comes at an unbelievable cost. In 2001, the National Highway Traffic Safety Administration (NHTSA, 2001) recorded 6,323,000 police-reported traffic crashes, in which 37,795 people died and 2,003,000 people were injured. When averaged, these statistics indicate that one police-reported traffic crash occurs every 5 seconds, an injury is sustained every 10 seconds, and a fatality occurs every 12 minutes. Fortunately, progress has been made in reducing the number of automotive-related deaths and serious injuries. In fact, despite the daunting statistics cited for 2001, the year marked a historically low fatality rate of 1.51 per 100 million vehicle miles of travel. These reductions are the result of a large-scale effort to improve roadway and vehicle safety (Dewar and Olson, 2001).

While the fatality rate has improved, it is important that readers do not become emotionally detached from the seriousness of the problem. Paul Dowd, the VP Operational Development at Newmont Mining Corp., addressed this issue in a keynote speech at the 2003 Human Factors & Ergonomics annual meeting, noting that his passion for safety was derived from mining tragedies (Dowd, 2003). He emphasized that it is essential that citizens digest the significance of fatality counts. After all, the death toll of the automotive transportation’s historically low annual fatality count is thirteen times greater than that of the September 11th catastrophe.

New technology is being developed to improve road safety and to continue the lowering trend. One technology, called a collision avoidance system (CAS), alerts drivers when their vehicle is heading for a collision based on the situation dynamics (Kiefer et al., 1999). The method in which these systems alert the driver is of considerable interest. Since the driving task involves extensive visual workload, CAS alerts that are perceived through non-visual senses may be more conspicuous to the driver. Their use would alleviate the attentional demand placed on drivers’ visual senses, thus allowing them to focus on the driving task. Consideration for the CAS alarm characteristics and reliability must be taken, since they will significantly affect how people react to these systems.

Kiefer et al. (1999) developed the functional interface requirements for a forward collision avoidance system. They modeled driver’s hard braking response to a braking lead vehicle to attain the proper timing of a CAS alert. The presentation of the alarm across the auditory, visual, and haptic (touch) modalities was tested. For the visual alert, an opaque alert icon with the capitalized word “WARNING” underneath was tested using a “high” head-down display and a head-up display. The auditory warning used a non-speech sound and a speech sound (the word “warning” repeated) that were played at 75 dBA through the front speakers. The haptic alert evaluated was a brief (600 ms) brake pulse, or “vehicle jerk” alert that decelerated the car at 0.24 g’s. The authors found that a forward collision avoidance system alert-interface requires a specific non-speech tone for auditory warning, while the use of a visual icon is recommended for visual warning. The brake pulse haptic alert showed promise, but was not made a requirement owing to unresolved issues with driver annoyance and confusion, and performance issues under slippery road conditions.

The design of collision-avoidance systems extends beyond front collision situations. Three-hundred-sixty degree monitoring can be envisioned through the use of headway distance sensors, forward obstacle-detection sensors, back-up aids, blind-spot sensors, and vehicle-lane position sensors (Najm, 1995). In order for these systems to effectively communicate collision warnings to drivers, an interface that integrates the information provided by these systems needs to be
developed. Two technologies that may help drivers discern the location of a threat are spatial audio and directional haptic feedback. Spatial audio relies on people's ability to localize the direction of a sound wave by using timing and intensity differences in the sound between the left and right ear. Directional haptic feedback relies on people being able to perceive different vibrations applied to their skin. Both spatial audio and haptic feedback technologies, including their respective capabilities and limitations, are examined in detail in chapter 2.

1.1. Purpose and Objectives

The purpose of this research effort is to investigate drivers’ ability to localize auditory and haptic seat alarms in terms of speed and accuracy. This research subsequently investigates subjects’ preferences towards the alternative alarms.

1.2. Research Questions

The following research hypotheses are stated with respect to the investigation of automobile drivers’ ability to localize auditory and haptic seat alarms:

1) The auditory alarm mode will yield faster choice response times than the haptic seat alarm mode.
2) The combination of a non-directional auditory alarm with a haptic seat alarm mode will yield faster choice response times than the haptic seat alarm mode on its own.
3) Older drivers will have increased choice response times to stimuli than younger drivers.
4) The haptic seat alarm mode will be more accurately localized than the auditory alarm mode.
5) The haptic seat alarm mode will improve the localizability of the auditory alarm mode when they are both used in combination.
6) The haptic seat alarm mode will reduce the number of front/back confusions committed in localizing the auditory alarm mode when they are both used in combination.
7) Older drivers will be poorer at localizing the alarm modes than younger drivers.
Literature Review

This chapter presents a review of the research literature relevant to the design of integrated collision avoidance system (CAS) interfaces. Specifically, spatial audio and haptic (vibration) displays are investigated. The first section of this chapter examines auditory alarm design. Issues pertaining to auditory signal detectability in noise, perceived urgency, response time, and annoyance are identified. The use of spatial audio displays to improve driver awareness of threat location is then presented. Application issues, such as the number of speakers, speaker location, and alarm parameters for optimal localization are discussed. The second section reviews the development of haptic display technology relevant to collision avoidance systems. Specifically, a haptic display that improves driver response time to warnings through directional cueing is highlighted. The chapter concludes that both spatial audio and haptic displays are opportune technologies for integrated collision avoidance systems.

2.2. Auditory Alarm Design

Kiefer et al. (1999) state that a forward collision avoidance system alert-interface requires a specific non-speech tone. An auditory alarm's parameters will play a role in dictating whether it is detected, how urgent the situation is perceived, how quickly drivers respond to the situation, and in what direction they are to look. A plethora of research has investigated what alarm parameters improve people's performance for each one of these research questions. However, few studies have attempted to determine what alarm parameters provide an optimal solution across all of these research questions. This section presents research findings applicable to auditory alarm design.

2.2.1. The Human Ear

The ear is the sensory organ that permits people to hear. People hear because the ear transforms acoustical energy in the environment into information. Three parts of the ear organ facilitate the transmission of sound information to the brain where it is perceived and interpreted: the outer ear, the middle ear, and the inner ear (Berger et al., 2000). The outer ear, which consists of the pinna and ear canal leading up to the eardrum, is responsible for modifying the acoustic wave before it hits the eardrum. The outer ear is described as a collector of sound since it amplifies certain sound frequencies, and attenuates others. Frequencies in the 2 to 4 kHz region are amplified by 10 to 15 decibels. As a result, people are most sensitive to sounds in this region. Each person's outer ear uniquely transforms the sounds arriving at the eardrum. This imprint is what people use to recognize and localize sounds in the environment.

The outer ear connects to the middle ear through the eardrum. The modified acoustic wave from the outer ear is converted into vibration of the eardrum. The purpose of the middle ear is to convert the motion of the eardrum in air to motion of the fluid in the inner ear. This is accomplished by means of a chain of three tiny bones: the hammer, the anvil, and the stirrup. The chain of bones inside the middle ear connects the eardrum to the oval window, or beginning of the inner ear. The chain allows vibrations of the eardrum to travel down to the inner ear. This is done
efficiently since the area of eardrum is about 17 times greater than the connection to the inner ear. This difference in area amplifies the pressure by this amount (Berger et al., 2000).

The inner ear transforms vibrations into nerve impulses to be perceived by the brain. The inner ear is a fluid filled enclosed chamber that is separated from the middle ear by the oval window. Motion in the oval window, driven by the vibrating stapes bone, creates a wave of movement that travels down the inner ear along the basilar membrane. The basilar membrane is narrower and stiffer at the base than at the apex. The rate of movement down the basilar membrane depends on how fast the oval window is pushed. A fast push, caused by higher sound frequencies, results in maximum displacement near the base, while a slow push, caused by lower frequencies, results in maximum displacement farther towards the apex. Thousands of inner hair cells line the basilar membrane. The deflection of the basilar membrane causes these inner hairs to bend, initiating nerve impulses. The firing of nerve impulses is affected by the frequency of the sound. High frequencies lead to nerve firings around the base of basilar membrane, while low frequencies lead to firings around the apex of the basilar membrane. This characteristic degrades as the intensity of the sound is raised. The central nervous system gathers information from both the rate of nerve firings and their location along the basilar membrane. The location of the vibrating hairs is predominantly used to interpret high frequencies, while the timing of the vibrating hairs is predominantly used to interpret low frequencies (Berger et al., 2000).

An explanation of how the human ear transforms acoustical energy in the environment into information was given. The next section describes a theory of how auditory information, as well as other sensory information, is perceived and interpreted by the brain.

2.2.2. Signal Detection Theory

Signal detection theory (SDT) (Green and Swets, 1966) explains situations in which people must decide whether some activation of their senses was caused by a signal or by some random process, such as background noise (Green and Swets, 1966). Upon sounding a signal, people can either decide that “Yes,” they heard a signal, or “No,” a signal was not presented. A 2x2 matrix depicting the possible combinations of the signal’s state and people’s response is presented below. (Wickens and Hollands, 1999).

<table>
<thead>
<tr>
<th>State of the World</th>
<th>Signal</th>
<th>No signal (Noise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>Hit</td>
<td>False Alarm</td>
</tr>
<tr>
<td>No</td>
<td>Miss</td>
<td>Correct Rejection</td>
</tr>
</tbody>
</table>

There are four joint events that are termed hits, misses, false alarms, and correct rejections (Green and Swets, 1966). A “hit” is when people correctly identify the presence of a signal, while a “miss” occurs when people do not detect a signal. “False alarms” occur when people erroneously believe that a signal is present, and “correct rejections” occur when people correctly state that a signal is not present.
Signal detection theory models this detection task into two stages of information processing (Wickens and Hollands, 1999). First, sensory evidence is compiled concerning the presence or absence of a signal. A decision is then made whether this evidence indicates a signal or not. When people hear a CAS alarm, it creates neural activity in their brain. The increase in neural activity is used as evidence to decide on the alarm’s presence. The greater the intensity of the signal, the greater the neural evidence. Let the variable X represent the amount of neural evidence in the brain. When the neural evidence, X, exceeds a criterion value of excitation, represented by Xc, people judge a signal to be present. If the signal does not cause X to surpass Xc, then people miss it (Wickens and Hollands, 1999). Figure 1 below illustrates this decision.

Background noise also contributes to the evidence variable X. If the amount of energy in the background noise is high, it is possible for the value of X to be similar to that generated by a signal. Random variations in the environment, and in people’s “baseline” level of neural activity associated with the sensory channels cause the amount of neural evidence to continuously vary. As a result of these two sources of variation, even when a signal is not present, X will sometimes exceed the criterion Xc. When this occurs, people believe a signal occurred and generate a false alarm. Accordingly, even when a signal does occur, the random level of activity may be low, causing X to be less than Xc. When this occurs, people miss the signal. The smaller the difference in intensity between signal and noise, or signal-to-noise ratio (S/N), the greater the chance that these errors will occur. The signal detection theory described to this point applies to signals presented in any modality. The effect of background noise within the ear specifically, and the effect it has on the detectability of an auditory signal, is termed masking, and is discussed in the next section.

**2.2.3. Masking**

Background noise in the signal-to-noise ratio can affect the detectability of an alarm in different ways. For example, an effect, called masking, occurs when a component of the background noise reduces the sensitivity of the ear to certain components or all of the alarm. Masking is the degree to
which a sound’s (the masked sound) audible threshold is raised by the presence of another (masking) sound (Sanders and McCormick, 1993). The audible threshold is the minimum sound intensity (measured in dB and also called sound pressure level [SPL]) of the signal that is required to hear the signal in the absence of noise in 50% of the trials in which it is presented. The masked threshold, on the other hand, refers to the sound intensity of the signal that is required for 75% correct detection of the signal on a two-interval task, where one of the two intervals consists of the signal and the noise, and the other contains only noise (Sanders and McCormick, 1993). Figure 2 illustrates the shift in the masking threshold on pure tones by a pure tone noise of 1200 Hz presented at 20, 40, 60, 80 and 100 dB. To account for masking effects, the CAS alarm volume may have to be raised when driving on a highway due to the increase in noise from the engine and wind. It has been found that in a controlled lab test scenario, a signal that is about 6 dB above the masked threshold will result in near perfect detection performance. However, a general rule to prevent masking effects in real world situations is to present the alarm 15 dB above the masked threshold (Karwowski and Marras, 1999).

![Figure 2. Masking effects of a 1200 Hz noise presented at 20, 40, 60, 80, and 100 dB on pure tones.](Taken from Sanders and McCormick, 1993. Printed with permission from McGraw-Hill, Inc.)

Good and Gilkey (1992) found that as a sound signal and noise are spatially separated along the horizontal plane, there is a significant increase in the signal’s detectability. This improvement in detectability is described as a “release in masking.” Good and Gilkey (1992) observed greater masking release at higher frequencies, but the effects are reduced or nonexistent for the low and middle frequency regions. This finding suggests that additional factors, such as the shape of the external ear, may play an important role in free-field masking.

Kawowski and Marras (1999) presents the following masking effect principles:

1. Direct masking, which occurs when a nonverbal signal is masked by a noise whose frequency is roughly the same as the signal’s frequency, yields the greatest increase in masked threshold.
2. If the signal and masking noise employ variations in pitch (tonal), the biggest masking effect is at the fundamental frequency of the masker and its harmonics. For instance, if the masking noise has a fundamental frequency of 1000 Hz, then an alarm that uses this frequency and its harmonics (2000, 3000, 4000 Hz, etc) should be avoided.

3. Increasing the SPL of the masking noise causes an increase in masked threshold of the signal. For reliable signal detection, a general rule is that the S/N ratio at the listener’s ear should be at least about 15 dB above the masked threshold.

4. The warning signal should not surpass the masked threshold by 30 dB in order to avoid interfering with verbal communication or annoying operators.

5. Increasing the SPL of the masker causes the masking effect to spread upward in frequency. Therefore, frequencies above the masker are often missed. This occurrence is termed the upward spread of masking. For example, masking noise from the road can spread upward to mask frequencies in the 1000 to 4000 Hz range. As a result, the alarm may need to be set at a lower frequency to avoid being masked. However, it should be noted that the ear is not as sensitive to lower frequencies.

6. Remote masking, which occurs when masking effects spread downward in frequency, can cause signal frequencies that are below those of the masker to be raised in threshold. Remote masking is usually not as significant as direct or upward masking.

7. Visual and haptic modalities should be considered as alternatives to auditory displays in extremely loud environments.

8. Masking effects on speech depend on a combination of complex factors. Therefore, predictions based on simple S/N ratios should not be relied upon.

9. Actual human speech is easier to understand in noise than is computer-generated speech.

This section shows how masking affects the perceptual process of detecting a signal. The next section discusses how attention demand may affect the cognitive process of signal recognition.

### 2.2.4. Effects of Attentional Demand on Signal Recognition

It is unclear whether attentional demands affect one’s ability to recognize an auditory signal. This section cautions the possibility in case the demands of the driving task do affect the recognition of certain alarms. Wilkins and Martin (1984) found that subjects showed decreased performance in recognizing a grinder alarm compared to a siren when attentional demand was devoted to playing a tennis video game. Both feedback and financial bonuses were provided to motivate participants to perform well. The grinder and siren were presented in conjunction with four other sounds that were set at various signal-to-noise ratios relative to a broadband\(^\text{a}\) background noise of 75 dBC\(^\text{b}\). The siren consisted of harmonic tones, while the grinder was more broadband and resembled the background noise. Wilkins and Martin (1984) speculate that the grinder sound had significantly lower attentional demand than the siren because the grinder signal had a lower contrast in frequency with the background noise. They infer that the existence and severity of this effect is dependent upon

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\(^\text{a}\) Broadband tones comprise of multiple frequencies, both high and low, across the frequency spectrum.

\(^\text{b}\) Weightings for SPLs have been developed to match people’s ears’ sensitivity to the pitch of sounds and to help judge the relative loudness of broadband sounds. The standard measure of the sound pressure level is dBA, since it approximates the sensitivity of the human ear at moderate sound levels. dBC weighted levels are used to evaluate sounds whose low-frequency components are responsible for secondary effects such as vibration.
spectral characteristics of the warning signal and its relation to the background noise. Therefore, if the warning signal has a high contrast with the ambient noise, then the effect of attentional demand is negligible. However, if the warning signal has a low contrast with the background noise, then inattention can reduce the signal’s recognizability. It should be noted, however, that Fidell (1985) disputes Wilkins and Martin’s interpretations, indicating that they are not persuasive since their measurements are imprecise and the effects reported are small.

2.2.5. Designing Urgency & Response Time into Auditory Alarms

A collision avoidance alarm should be designed to communicate the appropriate level of urgency to a driver and, where possible, to elicit the appropriate driver reaction in terms of response time and input selection. (Another important consideration, which will be discussed in the next section, is that the annoyance level of the alarm needs to fall within an acceptable range.) There is empirical evidence that certain parameters of a sound can be varied to achieve the desired level of urgency and response time. Haas and Casali (1993) investigated the perceived urgency and detection time of multi-tone and frequency-modulated warning signals for use in environments containing steady-state broadband machinery noise. Multi-tone alarms are comprised of several distinct pitches, while frequency-modulated alarms possess frequencies that change over time. Haas and Casali (1993) examined pulse format (sequential, simultaneous, and sawtooth frequency-modulated pulses), pulse level (65 dBC and 79 dBC), and time between pulses (0 ms, 150 ms, and 300 ms) for an auditory alarm in 68 dBC pink (equal energy at each octave) masking noise. Subjects performed a workload task that presented additional attentional demands during the signal detection task. The researchers found that as perceived urgency increased, detection time decreased. Moreover, louder pulses yielded greater perceived urgency and shorter detection times. Subjects rated sequential signals as less urgent than other pulse formats, and they took longer to detect their occurrence. In general, significant differences were not found between the perceived urgency or detection times of simultaneous and frequency-modulated pulses. The inter-pulse interval (time between pulses) only affected perceived urgency and had no significant effect on detection time. Reductions in the time between pulses yielded greater perceived urgency of the signal. These results suggest that CAS alarms should adopt higher pulse levels, use an inter-pulse time of 0 ms, and avoid sequential signals.

Haas and Edworthy (1996) expanded the parameters for designing alarm urgency and response time. They investigated the effects of pitch, speed, and loudness of auditory signals on both subjective perceived urgency and response time. Thirty college students between the ages of 18 and 40 with normal hearing participated in the study. Pulse fundamental frequency (200, 500, and 800 Hz), inter-pulse interval (0, 250, and 500 ms), and pulse level (5, 25, and 40 dB LIN SPL) were varied. The stimuli presented were 27 auditory signals that consisted of a train of four pulses. The duration of each pulse was 350 ms, with a 25 ms onset time and a 25 ms offset time. Onset time is the time from the start of the pulse to its maximum output, while offset is the opposite. They concluded that the signals with a high frequency, a fast speed and a high level of loudness produced the highest ratings of perceived urgency, as well as the fastest response times. Increasing any of these parameters yields an increase in perceived urgency. Increases in pitch and loudness were found to decrease response time. From this work, it can be said that to obtain the highest level of perceived urgency and shortest response time, one should employ a signal with the highest fundamental frequency (800 Hz), the shortest time between pulses (0ms), and the highest sound pressure level above ambient (40 dB LIN). Haas and Edworthy also state that designers who choose to follow
signal design recommendations of 15 to 30 db SPL above background noise could use signals with a fundamental frequency of 500 Hz or greater and a 0 ms inter-pulse interval.

The previous studies proved that a relationship exists between sound parameters and perceived urgency. However, the separation between the levels of perceived urgency was unexplored. Burt and Casali (1997) showed that modifying sound parameters facilitated magnitude estimation differences between low and medium urgency alarms, and low and high urgency alarms. Perception of an alarm’s low, medium, and high urgency levels, its classification within one of four groups, and its association with major work-related functions, was found to be possible after brief training on the alarm set’s various rhythmic patterns and pitch contours. The set consisted of twelve pulse alarms with interpulse intervals of various durations and linear onset and offset times of 20 ms. The onset and offset times for pulses less than 40 ms in length peaked in the middle. A pulse’s first harmonic was presented at 100%, while the second through fifth harmonics were presented at 50% of the fundamental frequency. The first pulse’s fundamental frequency was 523, 593, 675, or 635 Hz. The signal durations were not specified. This work strengthens the evidence that signal urgency connotations can be manipulated in a predictable manner by varying tempo patterns.

2.2.6. Alarms and Annoyance

The previously discussed research shows that the perceived urgency of an alarm can affect how quickly the driver responds to the system. However, if the alarm is perceived as annoying, the driver may ignore it, or even worse, may disable the system. Marshall and Lee (2003) examined how alert parameters and driving context affect perceived annoyance and urgency through three studies. Three groups of twenty-four subjects with normal hearing were divided across the three experiments. They were asked to envision driving context scenarios: a collision warning, a navigation alert, and an e-mail notification scenario upon the presentation of the alarm. Headphones were used to present the alerts in order to minimize background noise and to ensure uniform loudness. A multi-trait-multi-method analysis demonstrated the validity of urgency and annoyance as independent measures.

The first study looked at how alarm formant, duration of sound, and silence of an alert affect perceived urgency and annoyance. Formants are similar to harmonic series and are defined as a combination of several frequency regions irregularly distributed throughout the frequency spectrum, and of relatively great intensity. Four formants, comprising of 300Hz, 2550Hz, 3450Hz, and 4050Hz which were labeled high/i/, and 600Hz, 1350Hz, 2550Hz, and 3300Hz which were labeled high/a/, were used. Marshall and Lee (2003) found that the duration of sound increases perceived urgency more than it increases annoyance. Perceived annoyance is increased by a decrease in the duration of silence across all scenarios, with the e-mail notification having the least increase in perceived annoyance. They suggest that, for low-priority alerts, it is possible to increase perceived urgency without increasing the perceived annoyance of a signal by increasing its duration. The harmonic series affected perceived urgency and annoyance, with the high/a/ being the most urgent and annoying. The driving context mediates the effect of the harmonic series and the effect of the duration of sound and silence on perceived urgency and annoyance.

The second study explored the effects of sound onset (slow, fast), sound offset (slow, fast), and burst (i.e., several pulses with time intervals between pulses) density (three-pulse bursts, four-pulse
bursts) on perceived urgency and annoyance in the context of three driving scenarios. The sounds used for this study were modified versions of a rear collision avoidance alarm that had a frequency of 2,500 Hz and lasted 2.3 seconds. Marshall and Lee (2003) found that perceived urgency increased more than perceived annoyance when the fast onset and higher burst density was used. They suggest that manipulating the onset and burst density could increase perceived urgency without increasing the perceived annoyance of low-priority alerts. The effects of the sound parameters were mediated by the driving context scenario, with the largest effect occurring for the collision avoidance scenario.

The third study investigated how perceived urgency and annoyance are affected by the density (20%, 80%), burst speed (0.3775 s, 0.2275 s), and type (high /i/ sound from experiment 1, a frequency series used in experiment 2). Density refers to the percentage of the burst during which sound is present, where speed is the time from the beginning of one burst to the beginning of the next burst. Marshall and Lee (2003) found these three variables to have the greatest effect on perceived urgency and annoyance. Perceived urgency increased more than perceived annoyance when density increased. Perceived urgency also increased more than perceived annoyance for increased in burst speed. The frequency series alerts were rated as more urgent yet less annoying than the high /i/ alerts. The high /i/ alerts were actually found to be more annoying and less urgent than the frequency series alerts. They suggest that to create alerts with high levels of perceived urgency and low levels of perceived annoyance, designers should use a high-density, high-speed frequency series.

The literature mentioned thus far discusses sound parameters that facilitate quick response time and a high level of urgency. The next section discusses sound parameters that improve localization. Understanding these parameters may assist in designing alarms that induce rapid and desired responses.

2.3. Sound Localization

Jens Blauert (1997) defines sound localization as “the law or rule by which the location of an auditory event (e.g., its direction or distance) is related to a specific attribute or attributes of a sound event, or of another event that is in some way correlated with the auditory event.” Sanders and McCormick (1993) explain that people localize sound by relying on phase and intensity cues. Phase cues are based on interaural time differences (ITDs) of the sound between the left and right ear. Sounds directed towards the side of the head will reach the nearer ear 0.8 ms before the other ear, causing the sound heard at one ear to be out of phase with the sound heard at the other ear. This phase difference is effectively used to localize sounds with frequencies below 1500 Hz. Intensity cues are based on interaural intensity differences (referred to as interaural level or IID) between the left and right ear. A sound directed to the side of the head is perceived by the far ear as a lower intensity sound because of the auditory shadow cast by the head. Interaural intensity differences cannot help localize low frequencies since they diffract around the head, but they do help localize high frequencies greater than 3000 Hz. Localizing midrange sounds between 1500 and 3000 Hz is difficult, since both phase and intensity cues are insignificant for this range. Sounds that contain frequencies below 1500 Hz and above 3000 Hz, called broadband sounds, are thus suited for sound localization.
Makous and Middlebrook (1990) had six subjects, aged 24 to 34 years, indicate the apparent location of a 150 ms sound (1.8-16 kHz) in complete darkness by turning their head in its direction. Repeated measurement of the same stimulus location was also conducted to account for errors in the motor act of orienting the head. They found that people were able to accurately localize brief, broadband sounds located in front of them (horizontal and vertical errors were predominantly less than 5 degrees). People were also found to have a harder time localizing peripheral stimuli (maximum error of 20 degrees). Stimuli presented behind subjects were harder to localize than were frontal stimuli, partly due to the difficulty associated with turning one’s head around. Front/back confusions, in which a stimulus from the front is perceived as originating from the back, were observed in 6% of the trials. Makous and Middlebrook state that this finding suggests that people derive horizontal localization information principally from interaural intensity differences.

Abel et al. (1998) studied the ability of people between the ages of 10 to 79 years to identify the direction of sound. The sound was either a 1/3 octave noise band (achieved by dividing a broadband sound into three) centered at 0.5 or 4 kHz, or a broadband noise. The sound was played at 75 dB SPL, lasted 300 ms, and randomly emanated from a set of four or eight loudspeakers. Sixteen participants were screened for hearing loss in the region of 0.5 – 4 kHz. Abel et al. found that accuracy in sound speaker identification was highest when both phase and intensity cues were available from the broadband noise, and was lowest with the 1/3 octave noise band centered at 0.5 kHz owing to its absence of intensity cues. The study showed that interaural intensity differences with the 4 kHz sound were better for sound localization than were time-of-arrival differences with the 0.5 kHz sound. An overall trend towards poorer localization was found to exist with aging. Older people showed a decline in the use of phase cues and had greater difficulty with front/back discrimination.

This understanding of sound localization has led to interesting applications of its use. Perrot el al. (1996) examined the use of spatial sound in the visual acquisition of a target. Seven people, aged 22 to 33 years, with normal hearing and seeing abilities, participated in an aurally aided visual search task. A $40 bonus was offered to whoever achieved the fastest response time. The audio signal consisted of a broadband (0.3 kHz to 12 kHz) pink noise that emanated at approximately 70 dBA. The participant’s head was centered in a geodesic sphere that had 264 groups of LEDs positioned around it. One of 264 LED groups would be activated, and the participant would find and identify the target. Target locations ranged between plus and minus 180 deg in azimuth and from -70 to +90 degrees in elevation. Participants indicated whether an odd or even number of LEDs (three or two) were illuminated in the group by pushing one of two handheld push buttons. The sound originated from a speaker that was at the same location as the target LED group. The noise signals were delivered to the participant until they pushed the button. Perrot et al. found that search time within the central visual field was reduced by 100 to 200 ms when aurally directed assistance was provided. Major benefits were observed as the possible target locations appeared beyond the central visual field. For events in the rear field, reductions in search time exceeded 1000 ms. The researchers note that these searches were typically completed in 1250 ms, which is equal to the amount of time required to identify targets in the central visual field in the absence of an auditory cue.

Bolia et al. (1999) extended the work of Perrot et al. (1996) by varying the set size of spatial distractors in a free-field aurally aided search. Using the same apparatus, the target appeared among various distractors consisting of either one or three energized LEDs. The number of visual distractors present varied between 1, 5, 10, 25, or 50. Results confirm that the addition of a spatial
audio cue significantly decreases reaction time in a visual search task. Knowledge of how people localize sound has also led to applications in virtual audio space.

The development of virtual spatial audio cueing presented over headphones has shown promise. Using a software application, Begault (1993) evaluated the advantages of a virtual spatial auditory display in the visual acquisition of aircraft targets while under acceleration loads. The audio display spatially mapped a sound to the visual location of the target. Begault found that crew members were able to acquire targets approximately 2.2 seconds faster using the headphone spatial auditory display. Nelson et. al. (2001) examined the use of virtual spatial audio displays in dynamic situations. They tested people’s ability to localize a virtual sound source under various levels of sustained upward acceleration. Seven men and one woman, ages 23 to 30 years, who had prior experience with sustained acceleration experiments, participated in the experiment. Four of the participants had normal hearing, and four had a mild (≤ 10 dB HL) unilateral loss at 6 kHz. The stimuli consisted of broadband noise bursts presented through active noise reduction headphones. The stimuli were generated to emanate from varying positions in the horizontal plane and were continuously presented until the participant responded. An increase in localization error between 1.0 and 5.5 g was not found. However, a significant increase did occur at the 7.0 g level. They also observed that the percentage of front/back confusions was not significantly affected by upward acceleration.

Virtual spatial audio displays have also been tested under other bodily motion. Wu et al. (1997) investigated whether head movement improves the localization of sound in virtual spatial audio displays. Ten participants with normal hearing pointed out the direction of sound using a pointer while keeping their head fixed in one condition, then being allowed to rotate it in another condition. Wu et al. (1997) found that people are more precise in localizing virtual sound in space when their head is allowed to move (accuracy increased by 90%). There is also less front/back ambiguity.

### 2.3.1. Head Related Transfer Functions

In order to measure how people localize sound, the time it takes sound to transfer from the free-field to the person’s eardrum must be considered (Wu, Duh et al., 1997). The head related transfer function (HRTF) is a mathematical model of the time it takes a sound just outside the inner ear to reach the inner ear of an individual. The HRTF models the phase and intensity cues which occur between each ear and the changes in a sound’s frequency as it passes around and through the outer ear, head, and torso. Once modeled, the HRTF can code any sound position in auditory space. Each person has a unique HRTF, and though generic HRTFs have been developed, they typically fail to capture how people discern sounds coming from the front and back (Wenzel, 1995; Perrott, Cisneros et al., 1996; Bolia, D'Angelo et al., 1999). This failure is due to the fact that front/back localization relies heavily on one’s unique ear physiology (Makous and Middlebrooks, 1990).

Overall, the sound localization research discussed shows that free-field sound localization is possible if carried out in anechoic chambers. The next section identifies sound localization when sound reflections are present.
2.3.2. Sound Localization in Reverberant Chambers

Sound localization in small reverberant chambers is more complicated than free-field conditions. When a sound is emitted in a small chamber, it propagates outward and quickly reflects off the chamber’s surfaces (see Figure 3). As a result, the listener is exposed to multiple copies of the sound. The original sound, called the direct sound, is heard first since it arrives in a straight-line path to the listener. The reflected sounds are subsequently heard, and can be categorized as early reflections, reverberations, or echoes. Early reflections are sounds that arrive at the listener within the first 20 ms of the direct sound. Reverberation refers to a combination of later arriving reflections. These reflections have normally been scattered from many surfaces in the room. An echo is a late-arriving reflection that is so strong, or so isolated in time from other reverberations, it stands out as a discrete event in the midst of reverberation. Strong discrete reflections that ensue direct sounds by more than 50 ms will lead to an echo. The reflected sound waves are what make localization complicated in small chambers. The direct sound must compete with the various reflections for a listener to localize the sound source. However, localization in such situations is possible. The precedence effect states that the localization cues from the direct sound dominate those perceived from the reflections since it is heard first (Gilkey and Anderson, 1997). The precedence effect holds true even if the reflections are louder than the direct sound.

![Figure 3. Direct and reflected sound waves in a small reverberant chamber.](image)

The time between the direct and reflected sounds affects how the sound is perceived (Blauert, 1997). It has been found that if two sounds, which are both a single click of equal intensity, are emitted from different points in space and separated by 1 ms, then they are perceptually integrated and heard as one click appearing from a phantom location. This integration is termed summing localization. The phantom location appears from a position that is the average distance between the two physical sounds. Summing localization can occur between a direct and reflected sound if they are heard up to 1 ms apart (Blauert, 1997). Gilkey and Anderson (1997) note that the upper limit of summing localization duration is sometimes found to be as low as 0.5 ms instead of 1 ms. For delays between 1 and 4 ms, the precedence effect is optimal. The precedence effect begins to degrade for the range of delays between 5 and 10 ms. At this point, the second click begins to emerge as a second entity, and is heard as an echo.
The above describes how the precedence effect operates for instantaneous sound clicks. However, it is typical for everyday sounds to be extended in time, surpassing the gap in which their direct and reflected instances are heard. As a result, a wave of interference arises between the direct and reflected sound. The signal generated by their interference can lead to the perception of an entirely different cue location that can be unrelated to the position of the direct and reflected sound (Gilkey and Anderson, 1997). As a result, it is important to recognize the significance of the competition between direct and reflected sounds inside a reverberant chamber. The next section considers the application of sound localization specifically to CAS systems.

2.3.3. Spatial Audio Displays in Collision Avoidance Systems

The use of spatial sound, which can be described as an all-inclusive surround-sound technology, in collision avoidance systems is emerging. Tan and Lerner (1996) investigated people's ability to localize a free-field warning sound in a collision-avoidance system, as a means of indicating hazard location. Their research focused on the speed and accuracy of responses, the effects of sound type on performance, speaker location, and the use of speaker pairs to provide directional cues. Twenty-four subjects with normal hearing were seated in the driver’s seat of a stationary vehicle equipped with 12 audio system speakers located at various positions inside the passenger compartment. The twelve speakers allowed six warning sound stimuli to be presented from sixteen different directions using both single and double activation of speakers. The subject’s task was to determine the direction from which the sound was emanating and to indicate his or her response using a joystick mounted between the front seats. To prevent subjects from devoting all their attention to the localization task, subjects also watched a videotape of the forward view of a vehicle driving on a highway and verbally responded whenever a bridge was encountered. This task was also intended to keep the subjects’ heads somewhat stationary. Each participant’s head position was initially adjusted to be in the same position. The test vehicle was parked in an underground garage with the windows closed and the climate control and radio turned off.

Figure 4 on the next page illustrates that eight of the twelve speakers were mounted along the roofline of the vehicle with the intent of minimizing the effect of obstacles, such as headrests or occupants, in the sound path. Four speakers were mounted along a vehicle’s A-pillars (halfway between the dashboard and roof) and rear deck (inside the factory speaker openings). The twelve speakers were activated either individually or in combination yielding sixteen different directions. The speakers were hidden behind acoustically transparent fabric. (Note: Figure 4 is not a depiction of the actual test vehicle used, but rather illustrates the position of the speakers. The actual separation distances are not represented). Each of these speakers was aimed towards the subject’s head position (i.e., measurement position).
Seven stimuli were used in the experiment. They included three acoustic warnings, three voice warnings, and one additional stimulus (acoustic warning) used during the practice session. The three acoustic warnings included a low-fuel warning from an aircraft flight deck, an off-the-shelf warning buzzer from Radio Shack, and a repeating pattern warning incorporating several recommended warning characteristics from the literature. The three voice warnings included both digitized and synthesized voice samples repeating the word ‘DANGER.” Male and female digitized voices were selected for the digitized voice samples, while a male voice was selected for the synthesized voice sample. Each stimulus was repeated until the subject indicated the direction, using the joystick, from which the sound emanated.

Tan and Learner’s (1996) results can be broken down into four categories that are pertinent to the development of spatial audio displays for collision avoidance systems: 1) speed/accuracy in sound localization, 2) the acoustic warning format to use, 3) the optimal speaker orientation to use, and 4) the number of speakers to use.

2.3.4. Can Auditory Warnings be Rapidly and Accurately Localized?

Tan and Lerner (1996) used two measures of the speed of responding: response time (coarse movement of the joystick) and decision time (button press to indicate when the more precise orientation of the joystick was achieved). The response time measure is discussed here. Younger subjects responded with a mean response time of 0.95 s, while older subjects required about a half second longer. Both the particular sound and the particular speaker influenced the response time. The better performance conditions were found to be approximately 20% faster than the mean. Tan and Lerner conclude that initial orientation toward the signal can occur quickly. The authors note
that measuring a naturally occurring orienting response, such as eye movement in the direction of the signal, might yield even faster response times.

The best warning sound and speaker location performance gave mean localization errors of approximately 10 to 20 degrees. For some conditions, the overall mean error was just over 30 degrees. In addition, some errors exceeded 90 degrees, indicating confusion between front/back stimuli. Such confusion occurred in a few percent of cases for almost every sound/speaker condition. Tan and Lerner conclude that sound localization is accurate enough to orient the listener in the direction of the sound source, provided that appropriate sounds and speaker locations are chosen.

Kiefer, Hankey, and Fitch (2003) investigated drivers’ ability to quickly and accurately localize auditory and haptic alarms while driving on an open road. Sixteen subjects, balanced across age and gender, participated in the study. Subjects were screened for minimum hearing of 40 dB for 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, and 4000 Hz auditory tones, and maximum bilateral hearing differences of 10 dB. Four alarm modes were tested: 1) a production auditory alarm consisting of a 2000 Hz pure tone for the front locations and a 750 Hz pure tone for the side and rear locations, 2) a higher frequency broadband auditory alarm with embedded clicks for the front locations and a lower frequency broadband auditory alarm with embedded clicks for the side and rear locations, 3) a haptic seat that vibrated at 2 Hz, and 4) a combination alarm consisting of both the broadband auditory alarm and a haptic alarm that vibrated at 5 Hz. It was decided to further investigate the use of higher frequency auditory alarms for the front target locations and lower frequency auditory alarms for the rear target locations based on previous localization studies conducted internally at General Motors Corporation. The alarms were presented from eight target locations inside the vehicle: front-left, front, front-right, right, rear-right, rear, rear-left, and left. The auditory alarm target locations existed around the interior of the car cabin using the speakers from the vehicle’s stock sound system. The front, right, rear, and left target locations existed by using the principle of summing localization, which functions by simultaneously evoking two corner target locations. The haptic alarm target locations existed around the bottom of the driver seat. An eight-by-eight grid of haptic actuators was used to create eight different haptic alarms in the seat which mapped to the eight target locations around the vehicle. The experimenter evoked the alarms while the subjects drove along a two-lane highway. The experimenter recorded choice response time by pressing a button once the subjects began to verbalize the direction they perceived the alarm came from. Results indicated that subjects’ accurately localized 90% of the haptic alarms, 84% of the haptic and broadband auditory combination alarms, 34% of the broadband auditory alarms, and 27% of the pure tone auditory alarms. Subject mean choice response time significantly differed between the four alarms: subjects mean response time to the pure tone auditory alarm was 2.4 seconds, 2.3 seconds for the broadband auditory alarm, 2.2 seconds for the haptic alarm, and 2.0 seconds for the haptic and broadband auditory combination alarm. A Tukey multiple comparisons test revealed that response times were slower with the pure tone auditory alarm relative to the other alarms, and that response times were faster with the haptic and broadband auditory combination alarm relative to the other alarms. It should be noted that these mean response times included both correct and incorrect responses.
2.3.5. What Type of Warning Sound is Best for Localization?

The literature discussed earlier has shown that the certain parameters of the auditory alarm affect how quickly people respond to it and how well it is localized. For collision-avoidance systems, the alarm must perform well in both these areas. Tan and Lerner (1996) attempted to find an alarm that meets these criteria by evaluating seven CAS alarms.

The stimuli used by Tan and Lerner (1996) are presented below:

1. Low-fuel warning
   The low-fuel warning contained multiple frequencies, beginning at about 800 Hz and continuing upwards, and rapidly wails like a siren. The sound was designed for flight deck noise and was ranked best in warning effectiveness in a Tan and Lerner study (Tan and Lerner, 1996).

2. Off-the-shelf buzzer.
   The off-the-shelf buzzer was purchased at Radio Shack and is a sequence of a high and low frequency tones, with the repetition rate of 2.25 Hz.

3. Repeating pattern 1.
   The repeating pattern stimulus consisted of four pulses of approximately 110 ms each separated by 8 ms intervals. The four pulse pattern was repeated after 110 ms.

4. Repeating pattern 2 (practice session).
   This warning stimulus was a frequency modified version of the repeating pattern 1 and had the same repetition characteristics.

5. Digitized male voice.
   The digitize male voice saying the word “Danger” was taken from a 32 year old male who had broadcast radio speaking experience. The recording of the phrase was adjusted through software to a speech rate of 156 words per minute. The “signal sounded mature, formal, yet was not mechanical” (Tan and Lerner, 1996).

6. Digitized female voice.
   The digitized female voice was recorded from a 27 year old female with no formal broadcast speech training. The recording of the word “Danger” was adjusted through software to a speech rate of 156 words per minute.

7. Synthesized male voice.
   The phrase “Danger” was synthesized using a Sound Blaster 16 with Advanced Signal Processing (ASP) chip. The synthesized male voice characteristics were adjusted to match the desired speech rate of 156 words per minute. This voice sounded computer generated but was “very humanized” (Tan and Lerner, 1996).
Figure 5 shown below illustrates the younger subject accuracy scores of each sound that Tan and Lerner found for each speaker location. Their results show that the buzzer and repeating pattern 1 performed the worst for both speed and accuracy. The three voice messages and the low-fuel warning were roughly equivalent (although younger subjects responded to the low-fuel warning significantly faster than to other sounds). The buzzer and repeating pattern 1 were less accurately localized than were the other sounds (only by 5 degrees from the best performing low fuel sound). The voice warnings were generally well localized and were not significantly different than the low-fuel warning sound. The buzzer and repeating pattern 1 were affected by speaker location. Their performance was comparable to the other sounds for certain locations but was lower for other locations. Older subjects had a harder time localizing the buzzer and repeating pattern 1 sounds. The authors note that these were the sounds with narrower and higher frequency spectra, suggesting that these findings are quite possibly due to the effects of presbycusis, or age-related hearing loss. The authors conclude that among the six candidate alarms, alarm type had a modest though meaningful effect on sound localization. They suggest that once speaker location is taken into account, the alarm type chosen will be important. Overall, the low-fuel sound was found to be superior in performance to the buzzer and repeating pattern 1, while the differences among the three voice warnings were not as pronounced.

The following year, King and Oldfield (1997) found that signal bandwidth affects free-field auditory localization. Bandwidth was a concern since military aircraft audio displays typically have communication systems that are band limited in frequency response. As a result, King and Oldfield investigated the effects of limiting signal bandwidth on sound localization. The stimuli consisted of filtered white noise signals set at 65 dBA with the filter set to low pass all frequencies below 16 kHz. The researchers tested three participants and found that they lost the ability to accurately localize
elevation as the low-pass filter cutoff frequency approached 9 kHz. In addition, the participants could not effectively distinguish whether a signal had originated from in front of or behind their heads as the low-pass cutoff approached 7 to 9 kHz, and the high-pass filter approached, “10-13 to 16 kHz” (King and Oldfield, 1997, p. 294). King and Oldfield concluded that broadband signals encompassing frequencies from, “0 to (at least) 13 kHz” (King and Oldfield, 1997, p. 294) are required in order for listeners to accurately localize signals. Moreover, they determined that speaker quality for a spatial audio display must be taken into account.

The effects of alarm type have also been observed in traffic signal studies. Giguere et al. (2003) evaluated audible traffic signals for pedestrians with visual impairment. They were interested in finding which of six signals was the easiest and fastest to localize. Two of the signals investigated, the coo coo and the peep peep, were standardized by the Transportation Association of Canada, while the remaining four signals were variations of the melody signal proposed by the Institut Nazareth et Louis-Braille (Longueuil, QC). Objective sound localization measurements were made outside on a quiet street using a rotating chair as an angular pointer. Giguere et al. (2003) conclude that signals with the richest harmonic content are the easiest and fastest to localize.

2.3.6. Where Should the Speakers be Located?

The results of Tan and Lerner’s (1996) CAS audio display study provide preliminary insight on the optimal location of CAS speakers. A major finding from their study was that speakers 1, 3, 4, 5, 8, and 9 were responded to the fastest (see Figure 4). Speakers 1 and 9 were the best, while the speaker 13 combination performed the worst. In general, response times were fastest for speakers located either in front of or directly to the left or right of the subject. The speaker combinations (13, 14, 15, and 16) as a group were responded to slower than the other speakers, as were speakers located behind the driver.
Figure 4: Repeated

Tan and Lerner (1996) highlight the poorer performance of speaker 2 since its position is in the center of the windshield, and is a likely location for CAS designers to place an alarm. The poorer performance of the Speaker 13 condition is also notable since even though the speakers used for this combination ranked high independently, they performed worse than any other speaker condition when combined. However, speaker combination 14 had the greatest mean accuracy of all the speaker locations. In general, the speakers that were not aimed directly at the driver’s head position (10, 11, 12) did not perform as well. The findings suggest that integrated collision-avoidance systems should use individual speakers that are aimed directly toward the driver’s head.

2.3.7. How Many Speakers Should be Used?

The number of speakers used in an integrated collision avoidance system can be both advantageous and detrimental. For example, too few speakers will not support the existence of spatial audio, while too many speakers can increase localization error. As a result, the number of speakers to implement within a collision avoidance system is discussed in the following section.

Abel and Banerjee (1997) examined how the number of speakers, the separation angle between them, and the stimulus frequency (500 vs 4000 Hz) affected accuracy and choice response time. Twelve participants with normal hearing indicated the location of a 300 ms 1/3 octave noise band signal using switches arranged in the same configuration as the loudspeaker array. Abel and Banerjee found that accuracy decreases as the number of speakers increases and their separation decreases. They also found that response time increases with the number of speakers but remains unaffected by separation. The effect of frequency was relatively small. Signal detection theory (Green and Swets, 1966) was used to explain why there might be a decrease in localization accuracy when the number of speakers is increased. They assume that the actual free-field position in space is
the signal and that the other positions in space are noise. The degree of confusion over where a sound comes from will then depend on the signal-to-noise ratio. Therefore, the more speakers used to present a sound, the more noise exists from them, causing the signal-to-noise ratio to decrease. The S/N ratio is also assumed to decrease as the space between two positions in the azimuth decreases. Since smaller S/N ratios result in more misses (thinking the sound came from a noise position when it was actually the signal position) and more false alarms (thinking the sound came from the signal position, when it came from a noise position), it can be seen why increasing the number of speakers can be detrimental.

A year later, Abel et al.’s (1998) study of aging in sound localization, which was discussed earlier in this chapter, was found to complement signal detection theory. By investigating the effects of 4 versus 8 speakers on accuracy, they found that the greater the number of speakers in the array, the lower the percent correct. Of note, the four speaker array consisted of speakers placed either close to the midline or the interaural axis in each quadrant, while the eight speaker array consisted of speakers placed in pairs within each quadrant with distances between each pair varied at 15, 30, 45, or 60 deg.

Wallace and Fisher (1998) used information theory to suggest additional detrimental effects regarding an increase in the number of speakers. Information theory states that choice response time increases linearly with the average stimulus information or uncertainty. The theory originates from Hick (1952) and Hyman’s (1953) work. Hick varied the information content by varying the number of lights in the stimulus set from 2 to 10. Hyman expanded on this by varying information content through variations in the number of equi-probable alternatives, the relative probabilities, and sequential dependencies. Hick and Hyman both found a linear relationship between information content and response time. Wallace and Fisher (1998) decided to vary information content by using various speaker arrangements that could be used in practice for a spatial collision-avoidance system. Four arrangements were used to explore the relationship between information content, as determined by the number of speakers, and reaction time. Twelve participants identified auditory signals from one of two (front and back), three (front left, center, front right), four (front left, center, front right, and back), and six (front left, center, front right, rear-right, back, and rear-left) locations. At first, a linear trend was not found between information content and response time. However, when an additional “Speaker Confusion Pair” parameter was added to the linear model to account for front/back confusions by mapping speakers opposite each other in the frontal plane together, the model’s account for linearity increased from 14.2% to 95.1%. Results suggest that increasing the number of locations from which an alarm can sound, or placing the alarms symmetrically in front and in back of the driver, will increase response time to signal detection.

It should be noted that it is unclear in the research mentioned above whether the speakers were visible or not to the subject. The application of signal detection theory and information theory would suggest that speaker visibility is not an issue in determining response time, yet the relatively sparse validation of these theories leaves speaker visibility as a concerning factor.
2.3.8. Auditory Alarm Guidelines

Edworthy’s (1998) description of a good auditory alarm provides a summary set of guidelines. According to her research on medical alarms, a good auditory alarm has the following characteristics:

1) It attracts attention without startling people.
2) It is resistant to masking by other sounds.
3) It is relatively easy to localize.
4) Its meaning is clear.
5) Alarms used to convey emergencies sound more urgent than those that signal relatively unimportant, everyday functions.
6) It only sounds when risk or danger is present and does not give off false alarms. The reliability of an alarm is a key feature.
7) It is 15-35 dB above masked threshold in order to be easily detected.
8) It is between 70 and 75 dB to get attention.
9) Its acoustic structure is rich in harmonics within the 500-4000 Hz band so that masking does not occur and localization is easier. This way, when one of the harmonics is masked by another sound, the others will remain audible. Alarms rich in harmonics can also be played at lower signal-to-noise ratios than alarms that consist of only one or two harmonics. An alarm will also be easier to localize if it is rich in harmonics.
10) It informs of a problem, yet still allows communication to take place.
11) It could use everyday sounds to reduce the need to learn a set of ambiguous alarms.

These guidelines may apply well to CAS systems, especially considering the similar criticality between alarms used in the medical industry and alarms used for collision avoidance in transportation.

2.4. Haptic Feedback

Literally, the word haptic means relating to the sense of touch. However, in much of the human factors literature, the word haptic is used interchangeably to describe both tactile (i.e., touch) based sensations, kinesthetic sensations, and, frequently, vestibular based sensations. Tactile sensations are primarily skin based but also involve more interior sensors of contact and pressure. Kinesthetic sensation involves the detection of position and movement through proprioceptors in muscles, tendons, and joints (Kroemer, Kroemer et al. 1994). Vestibular sensation is based in the inner ear and detects acceleration in three axes. In the following discussion, the word haptic will be used to describe feedback methods, displays, devices, etc. that make use of any of these three more specific sensory modalities – tactile, kinesthetic, and vestibular.

The use of a haptic display for collision-avoidance systems appears promising. Transfer of information away from the visual modality to other modalities reduces visual demand. Additionally, scenarios involving visually demanding traffic conditions or loud passenger conversation, for example, might make the presentation of a visual or auditory alarm difficult to detect. A haptic alarm in such situations could provide unimpeded information delivery.
Laycock and Day (2003) examined recent developments and applications of haptic devices. Their work describes how haptic feedback has been combined with visual devices, such as virtual reality walls and workbenches, in order to improve their immersive experience. They identified the following requirements for any haptic feedback device:

1) The haptic device should allow unimpeded motion while still being able to exert high fidelity forces and torques. The mechanical constraints for the device should include low inertia, weight, and friction.
2) The haptic device should be statically balanced. This means that the center of mass of the moving parts remains stationary regardless of movement.
3) The haptic device should not intrude into the visual field.
4) The haptic device should be strong enough to take the stress and strain applied by the user and the actuators.
5) The haptic device should be compact and light. Consideration to the type of actuator should be taken.
6) The haptic device must be comfortable to use since it may be used for long periods of time.
7) The haptic device must match or exceed the human sensing resolution.

The next section reviews some of the haptic technology developments.

2.4.1. Haptic Developments

Haptic devices have been used since the 1970s as aids for visually and hearing-impaired people (Laycock and Day, 2003). Since then, the technology has grown to be incorporated into the computer-human interaction domain. Logitech’s tactile mouse, called the iFeel MouseMan, vibrates as the user interacts with buttons and menus on the desktop. This mouse was the first haptic device to be commercially available for the desktop environment (Laycock and Day, 2003). Haptic feedback has also been adapted by hand-held computers. Dosher et al. (2001) investigated the usefulness of haptic interfaces for such devices since their sheer size imposes severe constraints on the force output. They analyzed the lower limits at which haptic effects can be perceived by a human finger. By varying the amplitude, size, shape, and pulse-duration of a haptic vibration, they measured the smallest detectable effects. They found that haptic vibrations that follow a smooth shaped waveform result in a detection threshold approximately twice that of saw-tooth shaped waveform. This result suggests that the format of vibration can have a significant affect on its detectability. Mohellebi et al. (2001) successfully modeled perceived haptic feedback from the road for the inside of a vehicle simulator cabin. This was done using a vibrating seat and a motorized steering wheel. Results from the simulation verify that their model parallels data available in a vehicle experimental database. The authors state that the output torque represented in their model is equivalent to the torque exerted on the steering shaft of a car traveling at 45 mph.

The use of haptic technology inside vehicles is currently being explored. Enriquez et al. (2001) developed a steering wheel that included a pneumatic pocket covered with vinyl. The steering wheel was used to warn the driver when one of eighteen gauges displayed an error. Such errors were used to represent problems such as low fuel. The pneumatic pocket used a pump to produce pulsations of varying frequencies on the driver’s hands. While gripping the steering wheel, eleven subjects watched a graphical dashboard on one display and read sentences as they appeared on a second
screen. Subjects were asked to respond by hitting a key when a visual warning was displayed on the graphical dashboard. Feedback was provided through both the haptic steering wheel and visual display or just through the visual display. Subjects wore earplugs to ensure that noise from the pump was not cueing their response. The authors found that the subjects were able to detect warnings faster with both tactile and visual feedback compared to visual feedback alone.

Tijerina et al. (2000) evaluated the use of haptic feedback for rear-end collision-avoidance systems. They tested both a mono-pulse braking and an active steering display in a series of three small studies. The first study investigated jerk rate (0.08, 0.20, and 0.32 g/s) and duration (0.25, 0.65, 1.00 s) for a mono-pulse braking display. The second study examined the effects of active steering vibration frequency (4, 6, 8, 10, and 12 Hz), amplitude (1.2, 1.6, 1.8, and 2.2 Nm), and duration (0.50, 0.74, 1.00, 1.50, and 1.26 s) on display detectability and appropriateness ratings. In the third study, seven naive participants reacted to the mono-pulse braking display for two different simulated rear-end collision avoidance warning scenarios: a true positive (hit) condition, in which a lead vehicle was braking to a stop when the haptic braking display came on, and a false positive (false alarm) condition, in which the brake pulse occurred even though the lead vehicle was not slowing down. The results from the three studies show that for the given range in variables used, both displays practically yielded equivalent driver response. As a result, the authors recommend that haptic steering displays be reserved for collision avoidance situations that require steering maneuvers in order to maintain an intuitive mapping between the display and response. The authors suggest that the mono-pulse braking display should have a 0.32 g/s jerk rate applied for 0.65 seconds. The evaluation of the mono-pulse braking display revealed that drivers adjusted braking according to the constraints of the lead vehicle coming to a stop rather than according to the jerk rate or duration of the mono-pulse braking display. Inappropriate braking responses were also recorded in one-third of the false positive trials. Under these conditions, the authors generalize that drivers respond according to the situation rather than to the nature of the brake pulse.

2.4.2. Haptic Directional Cueing

Geldard et al. (1972) examined a perceptual tactile illusion they called the cutaneous “rabbit.” The authors varied generated tap pulses at different periods (2 ms duration each separated by 40 to 80 ms) at various spacings on the arm. The authors report that the inputs generate the perception of a progression of “hops” up the arm. If the temporal separation of the pulses is increased, the “hops” are perceived as covering a greater distance. The perception was observed with tap locations occurring between 2 cm and 35 cm apart. The number of pulses occurring in a location can impact the perception, with two pulses reported as too few, four to six pulses reported as better, and eighteen pulses reported as too many.

Based on the cutaneous rabbit phenomenon, Tan et al. (2003) developed a haptic display for the back using a 3-by-3 contactor array for displaying attentional and two-dimensional directional information to the user. The first study examined the extent to which haptic spatial cues can speed up or slow down an observer’s reaction time to detect a change in a visual scene. The observer was first tapped on the back and was then asked to detect a change between two similar visual scenes. Results show that reaction time decreased by an average of 41% (1630 ms) when the location of the contactor coincided with the quadrant of the visual scene where a change occurred. It was also found that reaction time increased by an average of 19% (781 ms) when the locations of the tapping
and visual change did not coincide. They suggest that haptic attentional cueing can be beneficial to a user who must attend to information in small areas within a large and complex visual display (e.g., an aircraft cockpit).

In the second study, the intuitiveness and discriminability of a set of directional lines imprinted on the subjects’ back using the haptic feedback was investigated. Sixteen subjects were asked to depict the sensations associated with two stimulus sets that differed in the number of contactors that were simultaneously activated. The first stimulus set used single line contactors, while the second used thick line contactors (see Table 1).

<table>
<thead>
<tr>
<th></th>
<th>Time 1</th>
<th>Time 2</th>
<th>Time 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Display</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>Thick Display</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Table 1. Haptic directional lines. (Tan, Gray et al., 2003)

The authors indicate that the thick display’s simultaneous activation of multiple contactors does not seem to enhance performance. It was found that naïve and minimally trained observers were able to discern the directions of a set of horizontal, vertical and diagonal directional lines with an overall accuracy of 81%.

These directional lines could be applied to haptic alerts in a collision-avoidance system or for directional cuing to inform the driver which direction to turn at the next intersection, thereby permitting drivers to keep their eyes on the road.

### 2.5. Literature Review Conclusion

This chapter presents a review of the research literature in both the auditory and haptic domains as they pertain to the development of an integrated collision avoidance system (CAS). Issues facing the design of auditory alarms revealed that careful consideration must be taken towards the environment in which the alarms are used. Noise from the road can raise the audible threshold of a CAS alarm in a variety of ways. However, presenting the alarm 15 dB above the masked threshold can assuage these effects (Karwowski and Marras, 1999). An alarm’s parameters, such as its frequency, duration, and interpulse time, can be manipulated to control its perceived urgency and response time. Certain modifications can even increase the alarm’s perceived urgency relatively more than its perceived annoyance. Designers of CAS systems should concern themselves with mapping the urgency of the situation invoking the alarm to the perceived urgency of the alarm. Further reductions in response
time to a CAS alert may be achieved by indicating the direction of the threat. Previous research investigated sound localization technology inside a stationary, as well as moving, vehicle. It has shown that sound localization can be performed with adequate accuracy and timing. Errors in localization are dependent on a variety of factors, and consideration for the alarm’s band frequency, the number of speakers in the display, the speaker location, and chamber in which the sound is played should be taken seriously.

The use of a haptic display for collision-avoidance systems also appears promising. Haptic feedback can transfer warning signals to the driver when their visual and auditory senses are overloaded. Haptic technology can also be used to provide attentional and directional cueing. It has been shown to decrease reaction time to visual alerts, as well as visual search response time. Overall, the integration of alarm design, sound localization, and haptic localization theory and applications builds a foundation for the design of integrated collision avoidance systems. Each domain is equally important to the mission of increasing vehicle and roadway safety, and reducing automotive fatalities.

### 2.6. Selection of Variables

The above review of auditory and haptic display research elucidates the selection of the following independent and dependent variables. The independent variables of gender and age are of interest in order to generalize the results of this transportation study to a broad user population. Although no gender differences are hypothesized regarding response time and accuracy, controlling for gender allows a robust exploration of subject preferences. Controlling for age is necessary owing to degraded accuracy and increased response time observed in older subjects. The target location independent variable allows investigation of which target locations are easier to localize, and which ones are confusing. The alarm mode independent variable allows the examination of both auditory and haptic alarms for automotive collision avoidance systems.

The dependent variables measure subject choice response time, accuracy and subject preference to the collision avoidance alarms. The choice response time measure facilitates the examination of how quickly subjects can identify the location of the alarms, while the accuracy dependent variable allows the measurement of whether subject responses are correct. Accuracy is assessed based on the percentage of correct target location identifications, as well as by the number of front/back confusions committed. The accuracy measure is important owing to the difficulties people have in localizing auditory alarms inside reverberant chambers cited in the literature. The number of front/back confusions committed is also important to measure owing to the severity of the implications a collision avoidance system has in directing a driver’s attention to the front of a vehicle when the collision is occurring in the rear. Subject preferences towards the alarm modes are gathered in order to subjectively assess each alarm mode. Feedback regarding alarm mode appropriateness allows the analysis of whether the intensity and duration of the alarm modes are adequate. Feedback regarding the directional information contained in the alarm modes allows the investigation of their ability to differentiate between adjacent target locations. Subject preferences towards the alarm modes under different hypothetical contexts are also investigated. Together, the observed subject preferences yield a subjective evaluation of the alarms designed for collision avoidance systems.
Methods

The methods used to investigate automobile drivers’ ability to localize auditory and haptic alarms in terms of speed and accuracy are introduced in this chapter. The experimental design is presented first. The subject selection criteria are then detailed. The chapter proceeds with a description of the experiment’s apparatus, which includes the roadway, test vehicle, and measurement systems. The chapter concludes with a description of the experimental protocol.

3.1 Experimental Design

This section identifies the experimental design utilized in this study. The independent variables are described first. The experimental design matrix and balanced Latin squares are then presented. The section ends by defining the dependent variables to be used.

3.1.1 Independent Variables

Between Subjects Variables

Gender (2)
   Male, Female

The gender independent variable was chosen in order to generalize the results of this transportation study to a broad user population. Gender may account for differences in driver preferences between the alarm modes.

Age (2)
   Younger (21-30 years old), Older (60-70 years old)

The younger and older age groups were selected to investigate the degradation in localization accuracy and increase in response time as people age. The performance of elderly drivers in localizing alarms is of interest owing to previously found degradation issues in auditory localization. Degradation in localization performance as well as an increase in response time is expected as age increases.

Within-Subjects Variables

Target Location (8)
   Front-Left, Front, Front-Right, Right, Rear-Right, Rear, Rear-Left, Left

The independent variable of target location was selected to provide insight on drivers’ ability to judge the location of the alarm modes across eight target locations. The absolute judgment task reveals which target locations are clearly identifiable, and which ones are vaguely identified.
Alarm Mode (4)
Auditory Alarm, Haptic Alarm, Auditory and Haptic Combination Alarm, and Non-directional Auditory and Haptic Combination Alarm

The alarm mode independent variable allows the investigation of four alarm modes. The auditory alarm mode tests the ability of the spatial audio display to direct driver’s attention. The haptic alarm mode tests the ability of the vibrating seat to direct driver’s attention. The auditory and haptic combination alarm mode tests whether there is a benefit in combining the two alarm modes together. The non-directional auditory and haptic combination alarm mode tests whether the changes in performance for the combination alarm mode, if any exist, are due to the spatial audio, or just the presence of an auditory alarm with the haptic alarm.

3.1.2 Experimental Design Matrix

Table 2 below illustrates the mixed-factor experimental design matrix utilized in this experiment. Subjects one through eight (S1 – S8) were younger females, while subjects nine through sixteen (S9 – S16) were elderly females. Subjects seventeen through twenty-four (S17 – S24) were younger males, while subjects twenty-five through thirty-two (S25 – S32) were elderly males.

Table 2. Experimental design matrix.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Target Location</th>
<th>Gender</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>20-30</td>
</tr>
<tr>
<td>Auditory</td>
<td>Front-Left</td>
<td>Female</td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Front</td>
<td></td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Front-Right</td>
<td></td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td></td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Back-Right</td>
<td></td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Back</td>
<td></td>
<td>S1-S8</td>
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<tr>
<td></td>
<td>Back-Left</td>
<td></td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td></td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Front-Left</td>
<td>Male</td>
<td>S17-S24</td>
</tr>
<tr>
<td></td>
<td>Front</td>
<td></td>
<td>S17-S24</td>
</tr>
<tr>
<td></td>
<td>Front-Right</td>
<td></td>
<td>S17-S24</td>
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<tr>
<td></td>
<td>Right</td>
<td></td>
<td>S17-S24</td>
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<td></td>
<td>Back-Right</td>
<td></td>
<td>S17-S24</td>
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<tr>
<td></td>
<td>Back</td>
<td></td>
<td>S17-S24</td>
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<tr>
<td></td>
<td>Back-Left</td>
<td></td>
<td>S17-S24</td>
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<tr>
<td></td>
<td>Left</td>
<td></td>
<td>S17-S24</td>
</tr>
<tr>
<td>Haptic</td>
<td>Front-Left</td>
<td>Female</td>
<td>S1-S8</td>
</tr>
<tr>
<td></td>
<td>Front</td>
<td></td>
<td>S1-S8</td>
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<tr>
<td></td>
<td>Front-Right</td>
<td></td>
<td>S1-S8</td>
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<td></td>
<td>Right</td>
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<td>S1-S8</td>
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<td></td>
<td>Back-Right</td>
<td></td>
<td>S1-S8</td>
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<td>S1-S8</td>
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<tr>
<td></td>
<td>Back-Left</td>
<td></td>
<td>S1-S8</td>
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<tr>
<td>Location</td>
<td>Group</td>
<td>Participants</td>
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<tr>
<td>Left</td>
<td>Male</td>
<td>S1-S8, S9-S16</td>
<td></td>
</tr>
<tr>
<td>Front-Left</td>
<td>Female</td>
<td>S1-S8, S9-S16</td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td></td>
<td>S17-S24, S25-S32</td>
<td></td>
</tr>
<tr>
<td>Front-Right</td>
<td></td>
<td>S17-S24, S25-S32</td>
<td></td>
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<tr>
<td>Right</td>
<td></td>
<td>S17-S24, S25-S32</td>
<td></td>
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<tr>
<td>Back-Right</td>
<td></td>
<td>S17-S24, S25-S32</td>
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<td>Back</td>
<td></td>
<td>S17-S24, S25-S32</td>
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<tr>
<td>Back-Left</td>
<td></td>
<td>S17-S24, S25-S32</td>
<td></td>
</tr>
<tr>
<td>Auditory and Haptic</td>
<td>Front-Left Female</td>
<td>S1-S8, S9-S16</td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td></td>
<td>S1-S8, S9-S16</td>
<td></td>
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<tr>
<td>Front-Right</td>
<td></td>
<td>S1-S8, S9-S16</td>
<td></td>
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<tr>
<td>Right</td>
<td></td>
<td>S1-S8, S9-S16</td>
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<tr>
<td>Back-Right</td>
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<td>S1-S8, S9-S16</td>
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<tr>
<td>Back</td>
<td></td>
<td>S1-S8, S9-S16</td>
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<tr>
<td>Back-Left</td>
<td></td>
<td>S1-S8, S9-S16</td>
<td></td>
</tr>
<tr>
<td>Non-directional Auditory and Haptic</td>
<td>Front-Left Female</td>
<td>S1-S8, S9-S16</td>
<td></td>
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<tr>
<td>Front</td>
<td></td>
<td>S1-S8, S9-S16</td>
<td></td>
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<tr>
<td>Front-Right</td>
<td></td>
<td>S1-S8, S9-S16</td>
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<td></td>
<td>S1-S8, S9-S16</td>
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<tr>
<td>Back-Right</td>
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<td>S1-S8, S9-S16</td>
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<td>Back</td>
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<td>S1-S8, S9-S16</td>
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<td>Back-Left</td>
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<td>S1-S8, S9-S16</td>
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<tr>
<td>Left</td>
<td></td>
<td>S17-S24, S25-S32</td>
<td></td>
</tr>
<tr>
<td>Front-Left</td>
<td>Male</td>
<td>S17-S24, S25-S32</td>
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<tr>
<td>Front</td>
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<td>S17-S24, S25-S32</td>
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<td>Front-Right</td>
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<td>S17-S24, S25-S32</td>
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<td>Left</td>
<td></td>
<td>S17-S24, S25-S32</td>
<td></td>
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</tbody>
</table>
### 3.1.3 Balanced Latin-Square

Figure 6 below illustrates the balanced Latin-Square utilized to fully balance the presentation order of the four alarm modes. The four columns are assigned twice in a row to evenly match the eight subjects.

<table>
<thead>
<tr>
<th>Mode Order</th>
<th>Participants 1-4</th>
<th>Participants 5-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>M2</td>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
<td>M3</td>
<td>M2</td>
</tr>
<tr>
<td>M3</td>
<td>M4</td>
<td>M3</td>
</tr>
<tr>
<td>M4</td>
<td>M1</td>
<td>M4</td>
</tr>
</tbody>
</table>

Figure 6. Alarm mode Latin-Square.

In order to balance the presentation of the target locations across the four alarm modes, the 8x8 Latin-Square shown in Figure 7 was broken down into four matrices. The target location order for the first alarm mode was derived from columns 1 and 2 in the 8x8 matrix. The target location order for the second alarm mode was derived from columns 3 and 4 in the 8x8 matrix. The target location order for the third alarm mode was derived from columns 5 and 6 from the 8x8 matrix. Finally, the target location order for the fourth alarm mode was derived from columns 7 and 8 from the 8x8 matrix. The resultant target location orders for the four alarm modes are depicted below.
3.1.4 Dependent Variables

The dependent variables selected to evaluate subject performance were mean choice response time, the percentage of correct target location identifications, and the percentage of front/back confusions committed. Driver preferences measured through questionnaires were also obtained.

Mean Choice Response Time

The choice response time was attained by measuring the time subjects took to verbally indicate the location of the alarm mode. Subjects identified the location of the alarm by calling out one of the eight target locations illustrated on a schematic of the automobile interior placed in front of them (see Figure 8). To avoid subjects delaying their responses by scanning the diagram for the appropriate terminology, they were asked to label the eight target locations using their own words prior to commencing the experiment. Choice response time was operationally defined as the time elapsed from the alarm mode being signaled and the first utterance evoked by the subject. Subjects were instructed to respond quickly while being as correct as possible. They were also discouraged from saying “uhm” when responding. In instances when they were unsure of the direction, they were asked to guess as quickly as possible.
Localization accuracy was measured using the percentage of correct target location identifications. A correct identification occurred when the target location indicated by the subject corresponded to the location from which the alarm mode was emitted. Subjects were instructed that the alarms could emanate from one of eight target locations by showing them a schematic of the car cabin.

Percentage of Front/Back Confusions Committed
The percentage of front/back confusions committed was attained by summing the number of target location identifications that were opposite in the frontal plane to the target location from which the alarm mode was evoked, and dividing this number by the total amount of possible front/back confusions. Front/back confusions occurred when subjects’ identified an alarm as coming from the back-left when it originated from the front-left, when they identified an alarm as coming from the front, when it originated from the back, and when they identified an alarm as coming from the front-right, when it originated from the back-right. Front/back confusions also occurred when subjects identified an alarm as coming from the back-left, when it originated from the front-left, when they identified an alarm as coming from the back, when it originated from the front, and when they identified an alarm as coming from the back-right, when it originated from the front-right.

Driver Preferences
Driver preferences towards the alarm modes were gathered using three questionnaires (see Appendix D). The first questionnaire investigated alarm mode appropriateness in order to assess whether their intensity and duration were adequate. The second questionnaire investigated the directional information contained in the alarm modes. This questionnaire assessed the ability of the alarm modes to differentiate adjacent target locations. The final questionnaire investigated driver preferences towards the alarm modes. This questionnaire assessed which alarm mode was preferred by having subjects rank them in relation to fifteen hypothetical situations. Together, these three questionnaires provided a subjective evaluation of the alarms designed to be used by collision avoidance systems.
3.2 Subjects

Thirty-two subjects participated in this study. Eight males and eight females were evenly selected from two age groups of 20-30 and 60-70 years of age. Prior to recruiting subjects, IRB approval was attained (see Appendix A). Subjects were recruited through the Virginia Polytechnic Institute and State University, local retirement communities, and contacts made through word of mouth. A general description of the study’s requirements was explained to the subjects prior to them coming in. Subjects were then screened with a verbal questionnaire to determine if they were licensed drivers and if they had any health concerns that should exclude them from participating in the study (see Appendix B). Once subjects came in, they signed an informed consent form (see appendix C). Each subject was screened for a minimal hearing level prior to taking part in the experiment. An ES-AM Earscan audiometric measurement system from Micro Audiometrics was used to plot an audiogram between the ranges of 0.1 kHz to 8 kHz. Subjects passed if they could detect frequencies between 0.5 kHz and 4 kHz at 40 dBA or less, while not surpassing a difference in the audible threshold of 10 dBA between the left and right ear (see Figure 9). Nine elderly males were prevented from participating as a result. Subjects were paid $20 per hour. They were allowed to withdraw at any time, and were told that if they did their compensation would be adjusted.

Figure 9. Audiometric evaluation.

3.3 Apparatus

This section explains the experimental apparatus. The research vehicle is identified. A description of the spatial audio and haptic seat systems is provided. The roadway used to collect data is then described. A map showing its geographical layout is included for added clarity.
3.3.1 Research Vehicle

The research vehicle consisted of a 2001 Buick LeSabre fitted with an integrated collision avoidance system (see Figure 10). The car provided feedback to the driver through both a spatial audio display and a haptic seat display. A description of these two displays is provided below.

![Figure 10. 2001 Buick LeSabre test vehicle.](image)

The spatial audio display consisted of four speakers that comprised the vehicle’s stock sound system. These four speakers were located in each corner of the vehicle cabin. The two front speakers were mounted on top of the vehicle’s dashboard, while the two rear speakers were mounted behind the back seats in the rear of the car. The spatial display was capable of generating eight sound locations through the use of summing localization. By simultaneously playing two speakers, a phantom sound location was generated that lied in the mean position between the two physical speakers. As a result, the front, right, back, and left sound locations were virtual. The timing of the two speakers were controlled using two soundcards ran by a computer in the trunk (see Figure 11)
The auditory alarm mode was balanced to 75 dBA for the eight target locations using binaural measurements with a head measurement system, or HMS (see Figure 12). This was conducted to ensure that subjects perceived each alarm to be the same volume given the variation in distances from each speaker to the subject. To calibrate the auditory alarms, the head measurement system recorded the sound level through microphones located in the left and right ear. The volume of the auditory alarm was then adjusted to 75 dB according to the measured volume discrepancy (see Figure 13).
The haptic seat display provided feedback through vibrations in the driver’s seat. Sixty-four actuators were embedded in the bottom of the driver seat in an 8x8 matrix (see Figure 14). The actuators were able to vibrate in groups to indicate eight directions to the driver: front-left, front, front-right, right, back-right, back, back-left, and left. An illustration of this is provided in section 3.4.2, which describes the haptic seat alarm mode. Drivers were not able to adjust the vibration intensity.

3.3 Roadway Description

The experiment took place on a two-lane highway in Blacksburg, Virginia. The experiment occurred in the wintertime, and trials were run during the daytime when conditions were clear. The experiment was postponed in the presence of snow or rain owing to the added danger as well as
road noise from driving in such conditions. The following map depicts the route utilized (see Figure 15). The route spanned eight miles along the 460, starting from Southgate drive and ending at the car pool parking lot off Highway 81. The duration of one lap was approximately sixteen minutes.

Figure 15. Test route consisting of an eight-mile stretch of two-lane highway in Blacksburg, Virginia.
3.4 Stimulus

The alarm modes used in this experiment consisted of both auditory alarms and haptic seat vibrations. The alarm modes were tested separately and in combination. A description of each alarm mode is presented below.

3.4.1 Auditory Alarm Mode

The auditory alarm mode consisted of a broadband sound played by the spatial audio display. Its frequency range spanned from 500 Hz to 7000 Hz. The sound comprised of five pulses that lasted 100 ms. The pulses were separated by 100 ms, and had a 20 ms onset and offset. Each pulse contained a sound impulse, or click, which was denoted by the sharp amplitude spike (see Figure 16). The spectrum analysis for the auditory alarm mode is provided below (see Figure 17).

![Figure 16. Auditory alarm sound wave.](image)

![Figure 17. Auditory alarm spectrum analysis.](image)
3.4.2 Haptic Alarm Mode

The second alarm mode was a haptic alarm that comprised a vibrating driver seat. The vibrating seat was able to produce eight different target locations: front-left, front, front-right, right, back-right, back, back-left, and left (see Figure 18). The haptic vibrations were presented at a frequency of 5 Hz. Each haptic alarm consisted of five pulses. The eight different haptic target locations, as they appear on the 8x8 actuator grid, are presented below. Each cell represents a haptic actuator.

![Figure 18. Haptic seat directional cues.](image)

3.4.3 Auditory and Haptic Combination Alarm Mode

The third alarm mode consisted of the auditory alarm used in conjunction with the haptic seat alarm. Both the sound and the seat vibration were simultaneously played. Both the sound and seat vibration comprised of five pulses and were played from the eight target locations.

3.4.4 Non-directional Auditory and Haptic Combination Alarm Mode

The final alarm mode also consisted of the auditory alarm used in conjunction with the haptic seat alarm. The difference was that the sound did not contain directional information since it was only played from the front target location within the vehicle. The haptic display, however, continued to convey directional information to the subjects. Both the sound and seat vibration were still played at the same time. The sound and seat vibration comprised of five pulses.
3.5 Procedure

Prior to driving, time was taken to orient subjects to the study, the vehicle, and the procedures. The test vehicle was prepared before the subjects used it. Checks were made to ensure that there was sufficient fuel. The vehicle was cleaned to ensure clear visibility. The passenger seat was also placed in the same position to minimize variance from sound reflections.

Prior to beginning each trial, the wind velocity was recorded from the local airport. Subjects were greeted and asked to show their driver’s license. The purpose of the study was explained and they then read and signed the informed consent (see Appendix C). An audiometric test was administered to ensure minimal hearing levels. Measurements of subjects’ height, weight, waist size, inseam length, and femoral length were measured.

A description of the spatial audio and haptic systems was given to the subjects. The fact that the warnings were manually triggered and not in response to on-road objects was made clear. A diagram of the vehicle’s interior was shown. Subjects were asked to label eight locations marked on the diagram using their own words. Subjects were instructed to quickly verbalize the location of the alarm using their terminology while being as correct as possible. Subjects were instructed to guess as quickly as possible if they were unsure of the target location. The subjects were told to refrain from saying “umm” prior to responding. Subjects were asked to voice the corner directions quickly. Using the front-left direction as an example, subjects were asked to say “front-left” without pausing in between saying “front” and “left”.

The subjects were then taken out to the experimental vehicle. They were seated and shown how to adjust the seat, the mirrors, and the steering wheel. Measurement of the distance across their thighs was taken. They were re-familiarized with the purpose of the study and their task. They were then asked to keep their heads in the same position as they normally would while driving. They were also asked to maintain a safe following distance behind lead traffic, and to not go over the posted speed limit of 55 mph. The experimenter then sat in the back-right passenger seat of the vehicle in order to administer the test trials (see Figure 19).
Once the vehicle reached cruising speed and was fully merged on the highway, subjects were given a chance to practice identifying the location of the alarms before each alarm mode session. Once the practice run was complete, subjects were informed that the experiment was about to begin. The experimenter then manually triggered the alarms using a keypad (see Figure 20). Pressing the “Enter” key triggered the alarms. Once the subject began to utter a response, the “0” key was then pressed to record their response time. Keys 1 through 9 (excluding #5) were mapped to the eight target locations. The experimenter pressed the corresponding key to record the subjects’ responses. Care was taken to not present the alarm modes while driving over a bridge in order to maintain consistent road noise levels. The alarm modes were also not presented while executing a turn in order to help ensure that the subjects’ heads remained in the same position (see Figure 21). At the end of each alarm mode session, subjects were asked to complete the alarm appropriateness questionnaire and the alarm mode directional information questionnaire. Once the questionnaires were completed, the experiment was resumed with the presentation of the next alarm mode. Once subjects experienced all four alarm modes, they were asked to complete the alarm ranking questionnaire.
At the end of the experiment, subjects were thanked for their participation and paid for their time. The data was copied to a floppy disk and transferred to a computer for analysis. The gas level of the vehicle was checked and the car was refueled if it had less than half a tank of gas.
Results

The goal of this research was to quantitatively assess driver’s ability to localize auditory and haptic alarms in terms of response time and accuracy, as well as to investigate driver preferences towards the alternative crash avoidance alarms. This chapter presents the results obtained regarding these performance measures.

The following approach was taken in analyzing the data. Performance data files for the thirty-two participants were concatenated into one Excel spreadsheet. This Excel file was then imported into the SAS statistical software application. SAS was used to conduct the various analyses presented in this chapter. Each SAS procedure was coded in the expression editor. The SAS code is presented in Appendix E. The SAS output was then exported to Microsoft Excel where it was graphed for visual inspection. General descriptive statistics, such as frequency counts and means, were conducted in order to ensure that the data had been properly aggregated and to facilitate familiarization.

This study collected both parametric and nonparametric data. The selection of which statistical methods to use was discussed amongst the advising committee. Additional advice on methods that analyze interactions in nonparametric data was obtained from the Virginia Tech Statistical Consulting Center.

The results chapter is broken into five sections. The first section presents the analysis of choice response time. The second section analyzes the percentage of correct identifications. The third section inspects the presence of speed-accuracy tradeoffs. The fourth section analyzes the percentage of front/back confusions committed. The fifth section presents the analyses of the three driver preference questionnaires.

4.1 Choice Response Time

The measured choice response times encompass the time taken for the experimenter to press a button once the subject initiated a verbal response. One response time data point was deemed invalid owing to the response button being accidentally pressed before the subject responded. The choice response time data was investigated using a generalized linear model analysis of variance in order to handle the unequal sample size (the reader is referred to Appendix E for the SAS code).

The balanced Latin square described in the methodology chapter was incorporated into the experimental design to prevent order effects. It was hoped that in doing so, sphericity, defined as the equality of variances of the differences between levels of the repeated measures factor, would be achieved (STATS-Website, 2003). However, as a precaution to any violations in sphericity, a Greenhouse-Geisser correction was used to evaluate the within-subject variables of target location and alarm mode. The choice response time ANOVA is presented below in Table 2. The main effects and interactions are discussed.
Table 3. The GLM Procedure for Repeated Measures Analysis of Variance For Response Time
Univariate Tests of Hypotheses for Within Subject Effects.

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<thead>
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<th>Source</th>
<th>DF</th>
<th>Type III SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
<th>G - G</th>
</tr>
</thead>
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<td></td>
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<td></td>
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<td>13160683.4</td>
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<td>0.1659</td>
<td></td>
</tr>
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<td>4673095.5</td>
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<td>0.4038</td>
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</tr>
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<td>3030809</td>
<td>0.47</td>
<td>0.5004</td>
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<tr>
<td>Error</td>
<td>28</td>
<td>182058466.4</td>
<td>6502088.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Within Subjects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>781052.24</td>
<td>4.22</td>
<td>0.0002</td>
<td>0.0016 *</td>
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<tr>
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<td>36305496.96</td>
<td>185232.13</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>3</td>
<td>17665587.78</td>
<td>5888529.26</td>
<td>11.71</td>
<td>&lt;.0001</td>
<td>&lt;.0001 *</td>
</tr>
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<td>1338164.22</td>
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<td>0.0534</td>
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<td>0.1686</td>
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<td></td>
<td></td>
</tr>
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<td>294735.77</td>
<td>2.16</td>
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<td>1023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* denotation of significant effects
4.1.1 Target Location Effect

Target location significantly affected choice response time (p = 0.0016). Figure 22 below illustrates the mean choice response time for each target location. A Tukey-Kramer multiple comparisons test reveals where the significant differences exist between the eight target locations. The back and front target locations yielded the fastest mean choice response times, 1.931 seconds (standard error = 0.044 seconds) and 1.948 seconds (standard error = 0.056 seconds) respectively. The corner target locations were responded to slightly slower: the back-left target location yielded a mean choice response time of 2.031 seconds (standard error =0.039 seconds), the front-left target location yielded a mean choice response time of 2.009 seconds (standard error =0.046 seconds), the back-right target location yielded a mean choice response time of 2.046 seconds (standard error =0.040 seconds), and the front-right target location yielded a mean choice response time of 2.024 seconds (standard error =0.040 seconds). The left and right target locations were responded to the slowest, with mean choice response times of 2.168 seconds (standard error = 0.050 seconds) and 2.110 seconds (standard error = 0.041 seconds) respectively.

![Graph showing choice response time for target location.](image)

Figure 22. Choice response time for target location.

4.1.2 Alarm Mode Effect

Alarm mode significantly affected the time subjects took to identify the target location (p < 0.0001). Subjects’ mean choice response time to the auditory alarm mode was 2.257 seconds (standard error = 0.035 seconds), while their mean choice response time to the haptic alarm mode was 1.968 seconds (standard error = 0.032 seconds). Subjects’ mean choice response time to the haptic and
auditory combination alarm mode was 1.987 seconds (standard error = 0.030 seconds). Their mean choice response time to the non-directional auditory and haptic combination alarm mode was 1.921 seconds (standard error = 0.026 seconds). Figure 23 below depicts the mean choice response times for each alarm mode. A Tukey-Kramer multiple comparisons test reveals that the auditory alarm mode was responded to significantly slower than the haptic, auditory and haptic combination, and the non-directional auditory and haptic combination alarm modes. There were no significant differences in choice response time between the three haptic alarm modes.

![Figure 23. Choice response time for alarm mode.](image)

### 4.1.3 Target Location by Alarm Mode Interaction Effect

There was a significant target location by alarm mode interaction (p = 0.0254). Table 4 below presents the mean choice response time for each target location and alarm mode. Figure 24 below shows how subject mean choice response time varied between the target locations for the four alarm modes.
Table 4. Mean choice response time for target location by alarm mode.

<table>
<thead>
<tr>
<th>Location</th>
<th>Alarm</th>
<th>Mean (ms)</th>
<th>Std Error</th>
<th>N</th>
</tr>
</thead>
<tbody>
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<td>76</td>
<td>64</td>
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<td></td>
<td>Haptic</td>
<td>2078</td>
<td>124</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Auditory + Haptic</td>
<td>2006</td>
<td>99</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>ND Auditory + Haptic</td>
<td>1852</td>
<td>50</td>
<td>64</td>
</tr>
<tr>
<td>Front</td>
<td>Auditory</td>
<td>2267</td>
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<td>64</td>
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<td></td>
<td>Haptic</td>
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<td>64</td>
</tr>
<tr>
<td></td>
<td>Auditory + Haptic</td>
<td>1865</td>
<td>104</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>ND Auditory + Haptic</td>
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<td>1959</td>
<td>82</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Auditory + Haptic</td>
<td>1960</td>
<td>64</td>
<td>64</td>
</tr>
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<td></td>
<td>ND Auditory + Haptic</td>
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<td>54</td>
<td>64</td>
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<td>Haptic</td>
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<td>2085</td>
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<td>64</td>
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<td>2249</td>
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<td>64</td>
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<tr>
<td></td>
<td>Auditory + Haptic</td>
<td>2024</td>
<td>84</td>
<td>64</td>
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<td>110</td>
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<td>ND Auditory + Haptic</td>
<td>2120</td>
<td>99</td>
<td>64</td>
</tr>
</tbody>
</table>
4.2 Percentage of Correct Identifications

The analysis of subjects’ localization accuracy begins with a report of the distribution of responses for each target location. This descriptive statistical analysis reveals the likelihood of each response for the eight target locations. The analysis also reveals the magnitude of the localization errors. The following eight diagrams show the percentage of subject responses for each alarm mode by target location. The confusion matrices associated with these graphs are presented in Appendix F.
4.2.1 Front-Left Target Location

The distribution of responses for the front-left target location is shown below in Table 5. Subjects correctly identified 61% of the auditory alarms, 84% of the haptic alarms, 91% of the auditory and haptic combination alarms, and 84% of the non-directional auditory and haptic combination alarms. Figure 25 on the next page illustrates the likelihood that subjects identify an alarm from the front-left as originating from the eight target locations.

Table 5. Distribution of responses for the front-left target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Front-Left</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>39</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>60.94</td>
<td>3.13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15.63</td>
<td>20.31</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>54</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>84.38</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15.63</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>58</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>90.63</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9.38</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>54</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>84.38</td>
<td>7.81</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7.81</td>
</tr>
<tr>
<td>Total</td>
<td>Frequency</td>
<td>205</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>34</td>
</tr>
</tbody>
</table>
Figure 25. Response likelihood for front-left target location.
### 4.2.2 Front Target Location

The distribution of responses for the front target location is shown below in Table 6. Subjects correctly identified 41% of the auditory alarms, 92% of the haptic alarms, 84% of the auditory and haptic combination alarms, and 89% of the non-directional auditory and haptic combination alarms. Figure 26 on the next page illustrates the likelihood that subjects identify an alarm from the front as originating from the eight target locations.

#### Table 6. Distribution of responses for the front target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Front-Left</th>
<th>Front</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>6</td>
<td>26</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>11</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>9.38</td>
<td>40.63</td>
<td>10.94</td>
<td>7.81</td>
<td>9.38</td>
<td>17.19</td>
<td>4.69</td>
<td>0</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>59</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>92.19</td>
<td>7.81</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>1</td>
<td>54</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>1.56</td>
<td>84.38</td>
<td>9.38</td>
<td>3.13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>57</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>89.06</td>
<td>7.81</td>
<td>1.56</td>
<td>0</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>Frequency</td>
<td>7</td>
<td>196</td>
<td>23</td>
<td>8</td>
<td>6</td>
<td>12</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

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Figure 26. Response likelihood for front target location.
4.2.3 Front-Right Target Location

The distribution of responses for the front-right target location is shown below in Table 7. Subjects correctly identified 38% of the auditory alarms, 81% of the haptic alarms, 84% of the auditory and haptic combination alarms, and 91% of the non-directional auditory and haptic combination alarms. Figure 27 on the next page illustrates the likelihood that subjects identify an alarm from the front-right as originating from the eight target locations.

Table 7. Distribution of responses for the front-right target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Front-Left</th>
<th>Front</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>0</td>
<td>3</td>
<td>24</td>
<td>19</td>
<td>14</td>
<td>3</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>4.69</td>
<td>37.5</td>
<td>29.69</td>
<td>21.88</td>
<td>4.69</td>
<td>1.56</td>
<td>0</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>2</td>
<td>1</td>
<td>52</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>3.13</td>
<td>1.56</td>
<td>81.25</td>
<td>14.06</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>2</td>
<td>0</td>
<td>54</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>3.13</td>
<td>0</td>
<td>84.38</td>
<td>12.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>58</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>90.63</td>
<td>9.38</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>Frequency</td>
<td>4</td>
<td>4</td>
<td>188</td>
<td>42</td>
<td>14</td>
<td>3</td>
<td>1</td>
<td>256</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>90.63</td>
<td>9.38</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 27. Response likelihood for front-right target location.
### 4.2.4 Right Target Location

The distribution of responses for the right target location is shown below in Table 8. Subjects correctly identified 9% of the auditory alarms, 78% of the haptic alarms, 72% of the auditory and haptic combination alarms, and 75% of the non-directional auditory and haptic combination alarms. Figure 28 on the next page illustrates the likelihood that subjects identify an alarm from the right as originating from the eight target locations.

Table 8. Distribution of responses for the right target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Front-Left</th>
<th>Front-Right</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>0</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>35</td>
<td>9</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0.00</td>
<td>9.38</td>
<td>12.5</td>
<td>9.38</td>
<td>54.69</td>
<td>14.06</td>
<td>0.00</td>
<td>6</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>50</td>
<td>10</td>
<td>0</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0.00</td>
<td>0.00</td>
<td>4.69</td>
<td>78.13</td>
<td>15.63</td>
<td>0</td>
<td>0.00</td>
<td>6</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>46</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0.00</td>
<td>0.00</td>
<td>7.81</td>
<td>71.88</td>
<td>20.31</td>
<td>0</td>
<td>0.00</td>
<td>6</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>48</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
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<td>Percent Correct</td>
<td>0.00</td>
<td>0.00</td>
<td>9.38</td>
<td>75</td>
<td>15.63</td>
<td>0</td>
<td>0.00</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>Frequency</td>
<td>0</td>
<td>6</td>
<td>22</td>
<td>150</td>
<td>68</td>
<td>9</td>
<td>1</td>
<td>256</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0.00</td>
<td>9.38</td>
<td>12.5</td>
<td>9.38</td>
<td>54.69</td>
<td>14.06</td>
<td>0.00</td>
<td>6</td>
</tr>
</tbody>
</table>
Figure 28. Response likelihood for right target location.
4.2.5 Back-Right Target Location

The distribution of responses for the back-right target location is shown below in Table 9. Subjects correctly identified 48% of the auditory alarms, 95% of the haptic alarms, 97% of the auditory and haptic combination alarms, and 95% of the non-directional auditory and haptic combination alarms. Figure 29 on the next page illustrates the likelihood that subjects identify an alarm from the back-right as originating from the eight target locations.

Table 9. Distribution of responses for the back-right target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>User Selection</th>
<th>Front-Left</th>
<th>Front-Right</th>
<th>Front</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>31</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>12.5</td>
<td>12.5</td>
<td>15.63</td>
<td>48.44</td>
<td>10.94</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>61</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.69</td>
<td>95.31</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>62</td>
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<td>1</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td>96.88</td>
<td>0</td>
<td>1.56</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>61</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.69</td>
<td>95.31</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Frequency</td>
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<td>8</td>
<td>17</td>
<td>215</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>256</td>
</tr>
<tr>
<td></td>
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<td>12.5</td>
<td>12.5</td>
<td>34.63</td>
<td>64.84</td>
<td>7</td>
<td>3.92</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Figure 29. Response likelihood for back-right target location.
4.2.6 Back Target Location

The distribution of responses for the back target location is shown below in Table 10. Subjects correctly identified 39% of the auditory alarms, 94% of the haptic alarms, 83% of the auditory and haptic combination alarms, and 86% of the non-directional auditory and haptic combination alarms. Figure 30 on the next page illustrates the likelihood that subjects identify an alarm from the back as originating from the eight target locations.

Table 10. Distribution of responses for the back target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>User Selection</th>
<th>Front-Left</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
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<td>15</td>
<td>10</td>
<td>3</td>
<td>8</td>
<td>25</td>
<td>3</td>
<td>64</td>
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<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>23.44</td>
<td>15.63</td>
<td>4.69</td>
<td>12.5</td>
<td>39.06</td>
<td>4.69</td>
<td>0</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
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<td>0</td>
<td>0</td>
<td>2</td>
<td>60</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
<td>3.13</td>
<td>93.75</td>
<td>1.56</td>
<td>0</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
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<td>2</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>53</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>3.13</td>
<td>0</td>
<td>1.56</td>
<td>12.5</td>
<td>82.81</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>55</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>1.56</td>
<td>0</td>
<td>3.13</td>
<td>9.38</td>
<td>85.94</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0</td>
<td>19</td>
<td>10</td>
<td>6</td>
<td>24</td>
<td>193</td>
<td>4</td>
<td>256</td>
</tr>
</tbody>
</table>
Figure 30. Response likelihood for back target location.
4.2.7 Back-Left Target Location

The distribution of responses for the back-left target location is shown below in Table 11. Subjects correctly identified 16% of the auditory alarms, 89% of the haptic alarms, 77% of the auditory and haptic combination alarms, and 88% of the non-directional auditory and haptic combination alarms. Figure 31 on the next page illustrates the likelihood that subjects identify an alarm from the back-left as originating from the eight target locations.

Table 11. Distribution of responses for the back-left target location.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
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<td>18</td>
<td>3</td>
<td>1</td>
<td>2</td>
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<td>10</td>
<td>1</td>
<td>1</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>6.25</td>
<td>28.13</td>
<td>4.69</td>
<td>1.56</td>
<td>3.13</td>
<td>39.06</td>
<td>15.63</td>
<td>1.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>57</td>
<td>2</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7.81</td>
<td>89.06</td>
<td>3.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>49</td>
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<td>64</td>
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</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td>18.75</td>
<td>76.56</td>
<td>3.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND Auditory +</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>56</td>
<td>0</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haptic</td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12.5</td>
<td>87.5</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4</td>
<td>18</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>50</td>
<td>172</td>
<td>5</td>
<td>256</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 31. Response likelihood for back-left target location.
4.2.8 Left Target Location

The distribution of responses for the left target location is shown below in Table 12. Subjects correctly identified 5% of the auditory alarms, 72% of the haptic alarms, 61% of the auditory and haptic combination alarms, and 67% of the non-directional auditory and haptic combination alarms. Figure 32 on the next page illustrates the likelihood that subjects identify an alarm from the left as originating from the eight target locations.

Table 12. Distribution of responses for the left target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>User Selection</th>
<th>Frequency</th>
<th>Front-Left</th>
<th>Front</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory</td>
<td></td>
<td>Frequency</td>
<td>5</td>
<td>18</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>27</td>
<td>7</td>
<td>3</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percent Correct</td>
<td>7.81</td>
<td>28.13</td>
<td>4.69</td>
<td>1.56</td>
<td>0</td>
<td>42.19</td>
<td>10.94</td>
<td>4.69</td>
<td></td>
</tr>
<tr>
<td>Haptic</td>
<td></td>
<td>Frequency</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>46</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percent Correct</td>
<td>6.25</td>
<td>0</td>
<td>1.56</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
<td>18.75</td>
<td>71.88</td>
<td></td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td></td>
<td>Frequency</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>9</td>
<td>39</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percent Correct</td>
<td>15.63</td>
<td>1.56</td>
<td>1.56</td>
<td>0</td>
<td>6.25</td>
<td>14.06</td>
<td>60.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td></td>
<td>Frequency</td>
<td>9</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>43</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percent Correct</td>
<td>14.06</td>
<td>3.13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15.63</td>
<td>67.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>28</td>
<td>21</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>31</td>
<td>38</td>
<td>131</td>
<td>256</td>
</tr>
</tbody>
</table>
Figure 32. Response likelihood for left target location.
4.2.9  Inferential Statistical Analysis of Percent Correct

In order to measure subjects’ ability to accurately localize auditory and haptic alarms, a validity score was computed for each trial. The validity score could take the form of either a hit or miss. A hit occurred when subjects identified the exact target location from which the alarm was triggered. A miss occurred when subjects incorrectly identified the target location from which the alarm was triggered. The validity data was categorical and required nonparametric statistical analyses to infer whether significant differences exist. A chi-square test was used to analyze the independent samples of age and gender, while a Cochran-Mantel-Haenszel test was used to analyze the related samples of target location and alarm mode. The effects revealed by these analyses are presented.

4.2.10  Age Effect

A Chi-Square test revealed that younger drivers (ages 20 to 30 years old) identify the location of the alarms significantly better than older drivers (ages 60-70 years old) (p < 0.0001). Figure 33 below illustrates the differences between younger and older drivers’ accuracy. Younger drivers correctly identified 77% of the target locations, while older drivers correctly identified 64% of the target locations.

![Figure 33. Percent correct for age.](image-url)
4.2.11 Target Location Effect

A Cochran-Mantel-Haenszel test found target location to be a significant main effect (p < 0.0001). Subjects correctly identified 51% of the alarms evoked from the left target location, 80% of the alarms evoked from the front-left target location, 77% of the alarms evoked from the front target location, 73% of the alarms evoked from the front-right target location, 59% of the alarms evoked from the right target location, 84% of the alarms evoked from the back-right target location, 75% of the alarms evoked from the back target location, and 67% of the alarms evoked from the back-left target location (see Figure 34 below).

![Figure 34. Percent correct for target location.](image-url)
4.2.12 Alarm Mode Effect

A Cochran-Mantel-Haenszel test found alarm mode to be a significant main effect (p < 0.0001). Subjects correctly identified 32% of the auditory alarms, 86% of the haptic alarms, 81% of the auditory and haptic combination alarms, and 84% of the non-directional auditory and haptic combination alarms (see Figure 35). Controlling for alpha inflation, post hoc comparisons between the four alarm modes revealed that significant differences lie between the three haptic alarm modes and the auditory alarm mode.

Figure 35. Percent correct for alarm mode.
4.2.13 Alarm Mode by Target Location Interaction Trend

Table 13 below presents the accuracy scores for each alarm mode and target location. The graphs constituting Figure 36 on the next page were observed and a trend towards an alarm by target location interaction was observed (no statistical test was performed). The accuracy scores for each alarm mode appear to depend on the target location from which they were presented. Presenting the alarms from the left and right target locations yields lower accuracy scores, whereas presenting the alarms from the back-right target location appears to increase accuracy scores.

Table 13. Percent correct for alarm mode by target location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Front-Left</th>
<th>Front</th>
<th>Front-Right</th>
<th>Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>39</td>
<td>26</td>
<td>24</td>
<td>6</td>
<td>31</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>60.94</td>
<td>40.63</td>
<td>37.5</td>
<td>9.38</td>
<td>48.44</td>
<td>39.06</td>
<td>15.63</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>54</td>
<td>59</td>
<td>52</td>
<td>50</td>
<td>61</td>
<td>60</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>84.38</td>
<td>92.19</td>
<td>81.25</td>
<td>78.13</td>
<td>95.31</td>
<td>93.75</td>
<td>89.06</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>58</td>
<td>54</td>
<td>54</td>
<td>46</td>
<td>62</td>
<td>53</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>90.63</td>
<td>84.38</td>
<td>84.38</td>
<td>71.88</td>
<td>96.88</td>
<td>82.81</td>
<td>76.56</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>54</td>
<td>57</td>
<td>58</td>
<td>48</td>
<td>61</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>84.38</td>
<td>89.06</td>
<td>90.63</td>
<td>75</td>
<td>95.31</td>
<td>85.94</td>
<td>87.5</td>
</tr>
<tr>
<td>Total</td>
<td>Frequency</td>
<td>205</td>
<td>196</td>
<td>188</td>
<td>150</td>
<td>215</td>
<td>193</td>
<td>172</td>
</tr>
</tbody>
</table>
Figure 36. Percent correct for alarm mode by target location.
4.3 Inspection for Speed-Accuracy Tradeoffs

The occurrence of speed accuracy tradeoffs was investigated. Figure 37 below diagrammatically shows the mean choice response time and percent correct values for each alarm mode and target location. It can be seen that the differences in performance between the auditory and haptic alarm modes were not due to subjects shifting their set for speed versus accuracy under the different conditions.

Figure 37. Inspection for speed-accuracy tradeoffs.
4.4 Percentage of Front/Back Confusions Committed

A front/back confusion is operationally defined as erroneously judging an alarm as coming from an opposite target location in the frontal plane. Front/back confusions have been shown to occur when localizing auditory alarms in the free-field (Makous and Middlebrooks, 1990). The target locations paired up for this measure are the front-left and back-left, front and back, and front-right and back-right. The measure is used to further describe how alarms are localized inside an automobile.

4.4.1 Target Location Effect

Target Location had a significant effect on the number of front/back confusions committed (Cochran-Mantel-Haenszel statistic, $p = 0.0293$). Figure 38 shows that subjects identified the alarms as coming from the back-left 3.91% of the trials that were evoked from the front-left. Subjects identified the alarms as coming from the back 4.69% of the trials that were evoked from the front. Subjects identified the alarms as coming from the back-right 5.47% of the trials that were evoked from the front-right. Subjects identified the alarms as coming from the front-right 3.13% of the trials that were evoked from the back-right. Subjects identified the alarms as coming from the front 7.429% of the trials that were evoked from the back. Subjects identified the alarms as coming from the front-left 1.56% of the trials that were evoked from the back-left.

![Figure 38. Percentage of front/back confusions committed for target location.](image-url)
4.4.2 Alarm Mode Effect

Alarm mode had a significant effect on the number of front/back confusions that occur (Cochran-Mantel-Haenszel statistic, \( p < 0.0001 \)). Figure 39 shows that subjects committed front/back confusions 16.15% of the auditory alarm trials. In contrast, subjects committed front/back confusions 0.26% of the haptic alarm trials, 0.52% of the auditory and haptic alarm combination trials, and 0.52% of the non-directional auditory and haptic alarm combination trials. Controlling for alpha inflation, post hoc comparisons between the four alarm modes revealed that significant differences lie between the three haptic alarm modes and the auditory alarm mode.

Figure 39. Percentage of front/back confusions committed for alarm mode.
4.4.3 Target Location by Alarm Mode Interaction Trend

Table 14 below presents the percentage of Front/Back confusions committed for each alarm mode and target location. Figure 40 below illustrates these front/back confusions. These graphs were observed and a trend towards an alarm by target location interaction was observed. Presenting the alarms from the back-left and back-right target locations yields lower front-back confusions, whereas presenting the alarms from the back target location appears to increase the number of front/back confusions.

Table 14. Percent of Front/Back Confusions for Alarm Mode by Target Location.

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Front-Left</th>
<th>Front</th>
<th>Front-Right</th>
<th>Back-Right</th>
<th>Back</th>
<th>Back-Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Frequency</td>
<td>10</td>
<td>11</td>
<td>14</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>15.63</td>
<td>17.19</td>
<td>21.88</td>
<td>12.5</td>
<td>23.44</td>
</tr>
<tr>
<td>Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.13</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>Frequency</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>0</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
</tr>
<tr>
<td>Total</td>
<td>Frequency</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Percent Correct</td>
<td>15.63</td>
<td>17.19</td>
<td>21.88</td>
<td>12.5</td>
<td>23.44</td>
</tr>
</tbody>
</table>
Figure 40. Percent of front/back confusions for target location.
4.5 Subject Preferences

Subject preferences regarding the four alarm modes were obtained through three questionnaires. The first questionnaire focused on the alarm modes’ appropriateness. The second questionnaire rated the directional information conveyed by the alarm modes. The final questionnaire asked subjects to rank the four alarm modes from best to worst across fifteen collision avoidance criteria. The results aggregated from the three questionnaires are presented in this section.

4.5.1 Alarm Appropriateness Questionnaire

The alarm mode appropriateness questionnaire asked subjects to rate the loudness and duration of the auditory component, as well as the intensity and duration of the haptic component for the applicable alarm modes. The reader is reminded that the auditory component format was not altered between the alarm modes; it only differed with respect to the location from which it was evoked from inside the vehicle cabin. As well, the haptic component format did not differ between the alarms. Subjects reported the loudness of the auditory alarm mode using the seven-point likert-type scale shown below in Figure 41.

![Figure 41. Auditory alarm loudness likert-type scale.](image)

Subjects reported the duration of the auditory alarm mode using the seven-point likert-type scale shown below in Figure 42.

![Figure 42. Auditory alarm duration likert-type scale.](image)
Subjects reported the intensity of the haptic alarm mode using the seven point likert-type scale shown below in Figure 43.

Figure 43. Haptic alarm intensity likert-type scale.

Subjects reported the duration of the haptic alarm mode using the seven-point likert-type scale shown below in Figure 44.

Figure 44. Haptic alarm duration likert-type scale.

The alarm mode appropriateness results are presented below in Table 15.

Table 15. Alarm mode appropriateness.
4.5.2 Alarm Directional Information Questionnaire

The directional information questionnaire gathered subject preferences regarding the alarms’ ability to indicate the direction of a crash threat. When asked whether the alarms are “a good method for allowing the driver to quickly determine the direction of the crash threat,” on average subjects responded that they “perhaps disagreed” with the statement for the auditory alarm mode (mean of 3.47 and standard deviation of 1.98 on the likert-type scale shown below in Figure 45), “perhaps agreed” to the statement for the haptic alarm mode (mean of 5.09 and standard deviation of 1.49), “moderately agreed” for the auditory and haptic combination alarm mode (mean of 5.66 and standard deviation of 1.12), and “moderately agreed” for the non-directional auditory and haptic combination alarm mode (mean of 5.62 and standard deviation of 1.10).

The directional information questionnaire also probed subjects’ preferences towards the alarms’ ability to differentiate adjacent target locations. Subjects used the above likert-type scale to respond to the eight target location differentiation questions shown below in Table 16.

Figure 45. Directional information likert-type scale.
Table 16. Directional information questions.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats on the front versus those on the front-left.</td>
</tr>
<tr>
<td>2.</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats on the front versus those on the front-right.</td>
</tr>
<tr>
<td>3.</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats on the front-left versus those on the left.</td>
</tr>
<tr>
<td>4.</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats on the front-right versus those on the right.</td>
</tr>
<tr>
<td>5.</td>
<td>Overall, this is a good method for allowing the driver to quickly distinguish between threats on the rear versus those on the rear-left.</td>
</tr>
<tr>
<td>6.</td>
<td>Overall, this is a good method for allowing the driver to quickly distinguish between threats on the rear versus those on the rear-right.</td>
</tr>
<tr>
<td>7.</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats on the left versus those on the rear-left.</td>
</tr>
<tr>
<td>8.</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats on the right versus those on the rear-right.</td>
</tr>
</tbody>
</table>
The mean response to each question is shown below in Figure 46. The graphs are arranged with respect to the target locations being contrasted.

Figure 46. Subject ratings of the alarm modes' ability to differentiate adjacent target locations.
**Directional Information Questionnaire ANOVA**

An analysis of variance was carried out on the subject responses to the previously listed eight questions. The model tested consists of a 2x2x4x8 mixed factor design. The independent variables are age, gender, alarm mode and target location differentiation question. The subject response dependent variable consists of interval data collected from the above likert-type scale. The ANOVA table is presented below in Table 17. From the ANOVA, the alarm mode, gender by target location differentiation question, and gender by target location differentiation question by alarm mode effects are significant.

Table 17. The ANOVA for subject perceptions regarding the alarm mode’s ability to differentiate adjacent target locations.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Subjects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>1</td>
<td>6.56640625</td>
<td>6.56640625</td>
<td>0.15</td>
<td>0.6984</td>
</tr>
<tr>
<td>Age</td>
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<td>19.140625</td>
<td>19.140625</td>
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</tr>
<tr>
<td>Gender x Age</td>
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<td>7.91015625</td>
<td>7.91015625</td>
<td>0.18</td>
<td>0.6708</td>
</tr>
<tr>
<td>Error</td>
<td>28</td>
<td>1199.992188</td>
<td>42.856864</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Within Subjects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Question</td>
<td>7</td>
<td>9.34375</td>
<td>1.33482143</td>
<td>1.7</td>
<td>0.1119</td>
</tr>
<tr>
<td>Question x Gender</td>
<td>7</td>
<td>16.13671875</td>
<td>2.30524554</td>
<td>2.93</td>
<td>0.0061 *</td>
</tr>
<tr>
<td>Question x Age</td>
<td>7</td>
<td>2.9375</td>
<td>0.41964286</td>
<td>0.53</td>
<td>0.8087</td>
</tr>
<tr>
<td>Question x Gender x Age</td>
<td>7</td>
<td>5.94921875</td>
<td>0.84988839</td>
<td>1.08</td>
<td>0.3777</td>
</tr>
<tr>
<td>Error (Question)</td>
<td>196</td>
<td>154.257813</td>
<td>0.78703</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>3</td>
<td>572.9765625</td>
<td>190.9921875</td>
<td>39.07</td>
<td>&lt;.0001 *</td>
</tr>
<tr>
<td>Mode x Gender</td>
<td>3</td>
<td>7.9726563</td>
<td>2.6575521</td>
<td>0.54</td>
<td>0.6538</td>
</tr>
<tr>
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<td>31.8046875</td>
<td>10.6015625</td>
<td>2.17</td>
<td>0.0978</td>
</tr>
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<td>9.4882813</td>
<td>3.1627604</td>
<td>0.65</td>
<td>0.587</td>
</tr>
<tr>
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<td>4.888486</td>
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<td>1.44</td>
<td>0.0947</td>
</tr>
<tr>
<td>Question x Mode x Gender</td>
<td>21</td>
<td>17.63671875</td>
<td>0.83984375</td>
<td>2.11</td>
<td>0.0027 *</td>
</tr>
<tr>
<td>Question x Mode x Age</td>
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<td>0.15141369</td>
<td>0.38</td>
<td>0.9948</td>
</tr>
<tr>
<td>Question x Mode x Gender x Age</td>
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<td>0.8</td>
<td>0.7153</td>
</tr>
<tr>
<td>Error (Question x Mode)</td>
<td>588</td>
<td>233.617188</td>
<td>0.397308</td>
<td></td>
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</tr>
</tbody>
</table>

* Denotation of significant effects
Alarm Mode Effect
Significant differences in subjects’ perceptions of the alarm modes’ ability to differentiate adjacent target locations exist (p < 0.0001). A Tukey multiple comparisons test reveals that subjects’ preferences to the auditory alarm mode are significantly different than the three haptic alarm modes. Averaging across the eight target location differentiation questions posed, subjects reported that they “perhaps disagreed” with the statements when questioned on the auditory alarm mode, while they “perhaps agreed” with the statements for the haptic, auditory and haptic combination, and non-directional auditory and haptic combination alarm modes. Figure 47 below depicts these results.

![Figure 47](image)

Figure 47. Subject preferences regarding the quality of the alarm mode's directional information.

Gender By Target Location Differentiation Question Interaction Effects
The ANOVA revealed that males’ agreeability to the eight target location differentiation questions was significantly different from females (p = 0.0061). However, this interaction needs to be interpreted by analyzing the gender by alarm mode by target location differentiation question interaction.
Gender By Alarm Mode By Target Location Differentiation Question Interaction Effect

The ANOVA also revealed that males' agreeability to the eight target location differentiation questions with regard to the four alarm modes was significantly different from females ($p = 0.0027$). Figure 48 below illustrates the subject mean responses. For the most part, females gave higher ratings for the directional information of the alarm modes than males.

Figure 48. Subject preferences regarding the quality of the alarm modes' directional information, broken down by gender, alarm mode and target location differentiation question.
4.5.3. Alarm Ranking Questionnaire

This section analyzes the ranking questionnaire administered after subjects experienced each alarm mode. The questionnaire asked subjects to rank the four alarm modes across fifteen collision avoidance related questions. For each question, a Friedman’s analysis of ranks test was used to analyze whether significant differences between the rank frequencies exist. Multiple comparisons between each alarm mode were made while controlling for alpha inflation to determine where the significant differences resided. The results for each question, along with an illustration of the rank frequencies, are presented below.

Question 1 – “Rank the Best Method for Presenting Crash Alerts to Drivers”

A Friedman’s analysis of ranks test revealed that significant differences in the rankings of the four alarm modes for question one exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 49 shows that subjects equally ranked the auditory and haptic combination alarm mode and the non-directional auditory and haptic combination alarm mode as the best alarm mode for presenting crash alerts to drivers (47% of the “ranked best” scores were given to both of the alarms). Subjects ranked the haptic alarm mode as the third best alarm mode (72% of the “ranked third best” scores were given to the haptic alarm mode), while subjects ranked the auditory alarm mode as the worst alarm mode (88% of the “ranked worst” scores were given to the auditory alarm mode).
Figure 49. Rankings given to the best alarm mode for presenting crash alerts to subjects.
Question 2 – “Rank the Most Noticeable Method in the Car”
A Friedman’s analysis of ranks test revealed that significant differences in the rankings of the four alarm modes for question two exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 50 shows that subjects equally ranked the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the most noticeable alarm modes in the car (41% of the “ranked best” scores were given to the non-directional auditory and haptic alarm mode and 38% of the “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the haptic alarm mode as the second most noticeable alarm mode in the car (63% of the “ranked third best” scores were given to the haptic alarm mode). Subjects ranked the auditory alarm mode as the least noticeable alarm mode in the car (75% of the “ranked worst” scores were given to the haptic alarm mode).

![Figure 50. Rankings given to the most noticeable alarm mode in the car.](image)

Table: Frequency Percent of Respondent Ranks for Alarm Mode

<table>
<thead>
<tr>
<th>Alarm Mode</th>
<th>Ranked Best</th>
<th>Ranked Second Best</th>
<th>Ranked Third Best</th>
<th>Ranked Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>13%</td>
<td>5%</td>
<td>6%</td>
<td>9%</td>
</tr>
<tr>
<td>Haptic</td>
<td>9%</td>
<td>9%</td>
<td>63%</td>
<td>22%</td>
</tr>
<tr>
<td>Auditory + Haptic</td>
<td>38%</td>
<td>41%</td>
<td>50%</td>
<td>13%</td>
</tr>
<tr>
<td>ND Auditory + Haptic</td>
<td>41%</td>
<td>41%</td>
<td>41%</td>
<td>16%</td>
</tr>
</tbody>
</table>
Question 3 – “Rank the Method that is Least Confused with Other Events Happening Either Inside or Outside of the Car”

A Friedman’s analysis of ranks test revealed that significant differences in the rankings of the four alarm modes for question three exists (Cochran-Mantel-Haenszel statistic based on rank scores, p = 0.0432). Figure 51 shows that subjects equally ranked the haptic alarm mode, the non-directional auditory and haptic combination alarm mode, and the auditory and haptic combination alarm mode as the alarm modes least confused with other events (34% of the “ranked best” scores were given to both the haptic alarm mode and the non-directional auditory and haptic alarm mode, and 28% of the “ranked best” scores were given to the auditory and haptic alarm mode). Subjects ranked the auditory alarm mode as the alarm mode most confused with other events (81% of the “ranked worst” scores were given to the auditory alarm mode).

Figure 51. Rankings given to the alarm mode that is least confused with other events happening either inside or outside the car.
**Question 4 – “Rank the Best Method for Getting My Attention Immediately If I was Distracted and not Concentrating on the Driving Task”**

A Friedman's analysis of ranks test revealed that significant differences in the rankings of the four alarm modes for question four exists (Cochran-Mantel-Haenszel statistic based on rank scores, p = 0.0023). Figure 52 shows that subjects ranked both the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the best alarm modes for getting their attention (41% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode and 38% of the “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects equally ranked the haptic alarm mode and the auditory alarm mode as the worst alarm modes for getting their attention (31% of the “ranked worst” scores were given to the haptic alarm mode and 66% of the “ranked worst” scores were given to the auditory alarm mode).

![Figure 52. Rankings given to the best method for getting subjects’ attention immediately if they are distracted and not concentrating on the driving task.](image-url)

Figure 52. Rankings given to the best method for getting subjects’ attention immediately if they are distracted and not concentrating on the driving task.
Question 5 – “Rank the Method that Startles Me the Least, that is, Cause me to Blink, Jump, or Make a Rapid Reflex-Like Movement”

A Friedman’s analysis of ranks test revealed that significant differences in the rankings of the four alarm modes for question five exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 53 shows that subjects ranked the haptic alarm mode as the least startling alarm mode (75% of the “ranked best” scores were given to the haptic alarm mode). Subjects equally ranked the auditory and haptic combination alarm mode, the non-directional auditory and haptic combination alarm mode, and the auditory alarm mode as the most startling alarm modes (9% of the “ranked worst” scores were given to the auditory and haptic alarm mode, 22% of the “ranked worst” scores were given to the non-directional auditory and haptic combination alarm mode, and 59% of the “ranked worst” scores were given to the auditory alarm mode).

Figure 53. Rankings given to the alarm mode that startles subjects the least.
**Question 6 – “Rank the Method that Interferes the Least with my Ability to Make a Quick and Accurate Decision about the Safest Driving Action to Take (Brake, Steer, Brake and Steer, or Do Nothing)”**

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question six exists (Cochran-Mantel-Haenszel statistic based on rank scores, $p < 0.0001$). Figure 54 shows that subjects equally ranked the haptic alarm mode, the non-directional auditory and haptic combination alarm mode, and the auditory and haptic combination alarm mode as the alarm modes that interfere the least with their decision making (44% of the “ranked best” scores were given to the haptic alarm mode, 34% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode, and 19% of “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the auditory alarm mode as the most interfering alarm mode (88% of the “ranked worst” scores were given to the auditory alarm mode).

![Frequency Percent of Respondent Ranks for Alarm](image)

Figure 54. Rankings given to the alarm mode that interferes the least with subjects’ ability to make a quick and accurate decision about the safest driving action to take.
Question 7 – “Rank the Method that Interferes the Least with My Ability to Perform a Quick and Accurate Emergency Driving Action”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question seven exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 55 shows that subjects equally ranked the haptic alarm mode, the non-directional auditory and haptic combination alarm mode, and the auditory and haptic combination alarm mode as the alarm modes that interfere the least with their ability to make quick and accurate emergency driving action (47% of the “ranked best” scores were given to the haptic alarm mode, 25% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode, and 22% of “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the auditory alarm mode as the alarm mode that interfered the most with emergency driving action (88% of the “ranked worst” scores were given to the auditory alarm mode).

"Rank the Method that Interferes the Least With My Ability To Perform a Quick and Accurate Emergency Driving Action"

Frequency Percent of Respondent Ranks for Alarm

![Rank Frequency Percent Chart](chart.png)

Figure 55. Rankings given to the alarm mode that interferes the least with subjects’ ability to perform a quick and accurate emergency driving action.
Question 8 – “Rank the Method that Least Annoys Me If the Alert Came On Once a Week in a Situation Where No Driving Action was Required”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question eight exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 56 shows that subjects ranked the haptic alarm mode as the least annoying alarm mode given that a false alarm occurs every week (75% of the “ranked best” scores were given to the haptic alarm mode). Subjects equally ranked the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the second least annoying alarm modes given a weekly false alarm (53% of the “ranked second best” scores were given to the non-directional auditory and haptic combination alarm mode and 31% of the “ranked second best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the auditory alarm mode as the most annoying alarm mode given a weekly false alarm (69% of the “ranked worst” scores were given to the auditory alarm mode).

Figure 56. Rankings given to the alarm mode that least annoys subjects given that a false alarm occurs weekly.
Question 9 – “Rank the Method that Least Annoys Me If the Alert Came On Once a Day in a Situation Where No Driving Action was Required”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question nine exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 57 shows that subjects ranked the haptic alarm mode as the least annoying alarm mode given that a false alarm occurs every day (75% of the “ranked best” scores were given to the haptic alarm mode). Subjects equally ranked the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the second least annoying alarm modes given a daily false alarm (53% of the “ranked second best” scores were given to the non-directional auditory and haptic combination alarm mode and 28% of the “ranked second best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the auditory alarm mode as the most annoying alarm mode given a weekly false alarm (66% of the “ranked worst” scores were given to the auditory alarm mode).

"Rank the Method that Least Annoys Me If the Alert Came On Once a Day in a Situation Where No Driving Action was Required"

Figure 57. Rankings given to the alarm mode that least annoys subjects given that a false alarm occurs daily.
Question 10 – “Rank the Method that Least Annoys My Passengers if the Alert Came On Where No Driving Action was Required”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question ten exists (Cochran-Mantel-Haenszel statistic based on rank scores, $p < 0.0001$). Figure 58 shows that subjects ranked the haptic alarm mode as the least annoying alarm to their passengers (84% of the “ranked best” scores were given to the haptic alarm mode). Subjects equally ranked the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the second least annoying alarm modes to their passengers (44% of the “ranked second best” scores were given to the non-directional auditory and haptic combination alarm mode and 41% of the “ranked second best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the auditory alarm mode as the most annoying alarm mode to their passengers (72% of the “ranked worst” scores were given to the auditory alarm mode).

Figure 58. Rankings given to the alarm mode that least annoys passengers if it came on where no driving action was required.
Question 11 – “Rank the Method that Appears the Least Out of Place in a Car or Truck”
A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question eleven exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0011). Figure 59 shows that subjects equally ranked the haptic alarm mode, the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the least out of place in a car or truck (56% of the “ranked best” scores were given to the haptic alarm mode, 19% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode, and 16% of the “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the auditory alarm mode as the most out of place in a car or truck (59% of the “ranked worst” scores were given to the auditory alarm mode).

Figure 59. Rankings given to the alarm mode that appears the least out of place in a car or truck.
Question 12 – “Rank the Best Method for Telling Me that I am in Danger and Need to React Immediately”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question twelve exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 60 shows that subjects equally ranked the non-directional auditory and haptic combination alarm mode and the auditory and haptic combination alarm mode as the best alarm modes for telling them that they are in danger (67% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode and 61% of the “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects equally ranked the haptic alarm mode and the auditory alarm mode as the as the worst alarm mode for telling them that they are in danger (34% of the “ranked worst” scores were given to the haptic alarm mode and 63% of the “ranked worst” scores were given to the auditory alarm mode).

"Rank the Best Method For Telling Me that I am in Danger and Need To React Immediately"

Figure 60. Rankings given to the best method for telling subjects that they are in danger and need to react immediately.
Question 13 – “Rank the Method that has the Greatest Potential for Presenting Crash Alert Information for Preventing Me From Getting in An Accident”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question thirteen exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 61 shows that subjects equally ranked the auditory and haptic combination alarm mode and the non-directional auditory and haptic combination alarm mode as the alarm modes that have the greatest potential for presenting crash alert information (50% of the “ranked best” scores were given to the auditory and haptic combination alarm mode and 44% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode). Subjects equally ranked the haptic alarm mode and the auditory alarm mode as the alarm modes with the least potential for presenting crash alert information (31% of the “ranked worst” scores were given to the haptic alarm mode and 66% of the “ranked worst” scores were given to the auditory alarm mode).

“Rank the Method that has the Greatest Potential For Presenting Crash Alert Information For Preventing Me From Getting in an Accident”

![Graph showing the ranking of different alarm modes](image)

Figure 61. Rankings given to the alarm mode that has the greatest potential for presenting crash alert information for preventing an accident.
Question 14 – “Rank the Best Method for Presenting Crash Alert Information that Gets My Attention without Being Overly Annoying”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question fourteen exists (Cochran-Mantel-Haenszel statistic based on rank scores, \( p < 0.0001 \)). Figure 62 shows that subjects equally ranked the non-directional auditory and haptic combination alarm mode, the auditory and haptic combination alarm mode, and the haptic alarm mode as the best alarm modes for presenting crash alert information without being overly annoying (38% of the “ranked best” scores were given to the non-directional auditory and haptic combination alarm mode, 31% of the “ranked best” scores were given to the auditory and haptic combination alarm mode, and 31% of the “ranked best” scores were given to the haptic alarm mode). Subjects ranked the auditory alarm mode as the worst alarm mode for presenting crash alert information without being overly annoying (75% of the “ranked worst” scores were given to the auditory alarm mode).

"Rank the Best Method for Presenting Crash Alert Information that Gets My Attention Without Being Overly Annoying"

![Bar chart showing the rankings of different alarm modes](image)

**Figure 62.** Rankings given to the best method for presenting crash alert information that gets subjects' attention without being overly annoying.
Question 15 – “If Your Vehicle Could Warn You of any Crash Threat Surrounding Your Vehicle, Which Method Would you Prefer to Have so that you Can Respond Quickly and Appropriately to the Crash Threat”

A Friedman’s analysis of ranks test revealed that significant difference in the rankings of the four alarm modes for question fifteen exists (Cochran-Mantel-Haenszel statistic based on rank scores, p < 0.0001). Figure 63 shows that subjects equally ranked the auditory and haptic combination alarm mode and the non-directional auditory and haptic combination alarm mode as the most preferred alarm modes (53% of the “ranked best” scores were given to the auditory and haptic combination alarm mode and 41% of the “ranked best” scores were given to the auditory and haptic combination alarm mode). Subjects ranked the haptic alarm mode as the third most preferred alarm mode (56% of the “ranked third best” scores were given to the haptic alarm mode). Subjects ranked the auditory alarm mode as the least preferred alarm mode (79% of the “ranked worst” scores were given to the auditory alarm mode).

"If Your Vehicle Could Warn You of Any Crash Threat Surrounding Your Vehicle, Which Method Would You Prefer To Have So that You Can Respond Quickly and Appropriately To the Crash Threat"

Figure 63. Rankings for the preferred method to have that allows subjects to respond quickly and appropriately to the crash threat.
Discussion

This thesis tested drivers’ ability to localize auditory and haptic alarms in terms of speed and accuracy. Subjects performed the localization task inside the acoustically complex environment of an automobile cabin while driving along a two-lane highway in light traffic. The effects of the selected parameters on choice response time, accuracy and driver preference are discussed in this section. An understanding of these effects will aid in the design of collision avoidance alarms.

5.1. Drivers’ Ability to Localize Alarms in Terms of Accuracy

Four research questions focus on how subjects’ accuracy levels in localizing auditory and haptic alarms. The first research question investigates the differences in localization accuracy using different peripheral sensory organs:

H1 - The Haptic Seat Alarm Mode Will be More Accurately Localized than the Auditory Alarm Mode

The first research hypothesis is supported. The haptic alarm mode was localized over two and half times more accurately than the auditory alarm mode. Subjects correctly identified 86% of the target locations using the haptic alarm mode, while only 32% of the target locations were correctly identified using the auditory alarm mode. A reason for the observed decrease in accuracy for the auditory alarm mode may be owing to categorization mistakes made in the perception stage of the human information processing model (see Figure 64 on the next page) (Wickens and Hollands, 1999). The categorization of which target location the auditory and haptic alarm modes come from is dependent on how discriminable the target locations are from each other. The results from the directional information questionnaire revealed that significant differences in subjects’ perception of the alarm modes’ ability to differentiate adjacent target locations existed (p < 0.0001). Subjects reported that they “perhaps disagreed” that the auditory alarm mode was good at differentiating adjacent target locations, while they “perhaps agreed” that the haptic alarm mode was good at differentiating adjacent target locations. Presuming these results indicate that the discriminability of the auditory alarm mode is less than the haptic alarm mode, Abel and Banerjee’s (1997) application of signal detection theory (Green and Swets, 1966) to target localization can explain the observed differences in accuracy.
Figure 64. A model of human information processing stages. (Taken from Wickens and Hollands, 1999. Printed with permission from Pearson Education)

Following Abel and Banerjee (1997), the target location used to evoke the alarm is assumed to be the signal and the other target locations are assumed to be noise. The degree of confusion over where the alarm comes from will then depend on the signal-to-noise ratio. The less discriminable a signal target location is from an adjacent target location, the more noise exists from it, causing the signal-to-noise ratio to decrease. A smaller signal-to-noise ratio means that the probability of a miss (thinking the alarm comes from a noise target location when it is actually the signal target location) is greater. Using this rendition of signal detection theory, the differences in accuracy between the auditory and haptic alarm modes may be due to the degree of overlap between the signal and noise target location distributions. Subjects are poorer at localizing the auditory alarm mode because there is more overlap between the signal and noise target location distributions, or a smaller signal-to-noise ratio (see Figure 65). As a result, there is a higher probability of attaining a “miss,” and a lower probability of attaining a “hit.” The haptic alarm mode, on the other hand, has less overlap between the signal and noise target location distributions, or a higher signal-to-noise ratio (see Figure 67). As a result, there is a lower probability of attaining a “miss,” and a higher probability of attaining a “hit.” The increased probability of a “hit” is the reason why it is more accurately localized.
Figure 65. Auditory alarm target location signal vs. target location noise.

Figure 66. Haptic alarm target location signal vs. target location noise.
The behavior of sound waves inside the vehicle may be another reason why the auditory alarm yields lower accuracy scores. Owing to the reverberant characteristics of the vehicle cabin, the direct sound must compete with its reflections in order for its location to be properly perceived. The sound reflections from the seats, dashboard, roof, and floor of the vehicle cabin all contribute to noise. Applying signal detection theory in its natural sense, the directional cues imbedded in the auditory signal are harder to perceive owing to the reduced signal-to-noise ratio resulting from the existence of this noise. Although the precedence effect (Gilkey and Anderson, 1997) states that the localization inside a reverberant chamber is possible since the cues from the direct sound dominate those perceived from the reflections, a certain amount of error occurs. For the task of making quick localization decisions, confusion between the direct and reflected sounds was observed. The haptic alarm mode, on the other hand, is not obscured since it does not emit reflections. As a result, it is easier to localize owing to its lower signal-to-noise ratio.

In chapter 2, Tan and Lerner’s (1996) investigation of spatial auditory displays for vehicle collision avoidance systems was reviewed. They conclude that sound localization is accurate enough to orient the listener in the direction of the sound source, provided that appropriate sounds and speaker locations are chosen. They report that the best warning sound played from the right target location (which comprised of the front-right and back-right speakers, positioned in the cabin roofline, being simultaneously played) had a mean localization error of approximately 10 to 20 degrees. Yet, since some target locations produced very poor performance, the overall mean error was just over 30 degrees. The results from the present study also indicate that the auditory alarm mode is better localized for certain target locations than others. However, in contrast with Tan and Lerner’s findings, the best accuracy score yielded by the auditory alarm mode is 61% for the front-left target location. One reason why this target location is not the same as the one reported by Tan and Lerner may be that the speakers comprised of the vehicle’s stock sound system and were not mounted in the roofline. Mounting the speakers in the roofline may have resulted in less obstructing sound reflections, leading to greater localization performance. Under the conditions tested, the average accuracy score for the auditory alarm mode is 33%.

The second research question investigates the addition of a haptic component to the auditory alarm:

**H2 - The Haptic Seat Alarm Mode Will Improve the Localizability of the Auditory Alarm Mode when they are Both Used in Combination**

The second research hypothesis is supported. The auditory and haptic combination alarm mode was localized two and half times more accurately than the auditory alarm mode. Subjects’ correctly identified 81% of the target locations using the auditory and haptic combination alarm mode, while only 32% of the target locations were correctly identified using the auditory alarm mode. A reason for the marked accuracy differences may be due to the resolution of adjacent target locations that the haptic alarm mode provides to the auditory alarm mode. The redundant perception of the target location through both the auditory and haptic modalities allows subjects to aggregate the directional information from both modalities. Any perceptual discrepancies that arise in using the auditory modality are alleviated by alternatively utilizing the haptic modality.

There does not appear to be a redundancy gain, however, in using both the auditory and haptic alarm modes to direct subject’s attention. The accuracy score of the auditory and haptic alarm mode (81% correct) is not significantly different from the accuracy score yielded by the haptic alarm mode (86% correct). These results suggest that subjects simply rely on the haptic alarm mode when
concurrently localizing the two alarms. The same can be said for the non-directional auditory and haptic combination alarm mode since subjects correctly identified 84% of the evoked alarms. A redundancy gain may exist, however, for alternative driving situations. It is possible that the presence of the auditory alarm mode may affect the localization of the haptic alarm mode if the driver is inattentive or fatigued. The context in which the alarms are utilized may play a roll in their overall effectiveness.

The third research question conjectures that the haptic component would resolve human limitations in localizing the auditory alarm mode.

\[ H3 - \text{The Haptic Seat Alarm Mode Will Reduce the Number of Front/Back Confusions Committed in Localizing the Auditory Alarm Mode When They are Both Used in Combination} \]

The third research hypothesis is supported. The alarm mode used has a significant effect on the number of front/back confusions that occur (Cochran-Mantel-Haenszel Statistic, \( p < 0.0001 \)). Subjects committed front/back confusions during 16.15% of the auditory alarm mode trials, and only 0.52% during the auditory and haptic combination alarm mode trials. A reason why subjects committed significantly more front/back confusions in responding to the auditory alarm mode may be because the front and back auditory stimuli have equivalent interaural time cues. Makous and Middlebrook (1990) suggest that subjects must rely on interaural intensity cues to resolve the location of such stimuli. Since the quality of the directional cues is diminished, more localization errors are observed. The localization cues present from the haptic alarm mode, however, make up for the vague auditory cues. As a result, the distinction between front and back target locations becomes clearer.

The presence of front/back confusions is not confined to this study. Tan and Lerner (1996) observed that some target locations produced errors exceeding 90 degrees. This confusion between front/back stimuli was observed in a few percent of cases for almost every sound/speaker condition. Makous and Middlebrook’s (1990) investigation of sound localization in the free-field reported that front/back confusions were observed in 6% of the trials. The ability of an alarm to allow drivers to discern between front and rear target locations may be of importance to the system’s overall effectiveness, but this may be somewhat offset by the driving context (e.g., the driver’s direction of travel).

The fourth research question investigates age effects on localization accuracy:

\[ H4 - \text{Older Drivers Will Have Reduced Accuracy to Stimuli Then Younger Drivers} \]

The fourth hypothesis is supported. Younger subjects (ages 20 to 30 years old) are significantly better at identifying the location of the alarms than older subjects (ages 60 to 70 years old) (\( p < 0.0001 \)). Younger subjects correctly identified 77% of the target locations, while older subjects correctly identified 64% of the target locations. The marked differences in accuracy observed suggest that there is a decrease in people's ability to categorize the location of auditory and haptic stimuli with age. These results are in agreement with the results Abel et al. (1998) reported from their study on the ability of people between the ages of 10 to 79 years to identify the direction of sound. They also found that localization error increases with aging.
5.2. Drivers’ Ability to Localize Alarms in Terms of Response Time

The remaining three research questions focus on how quick subjects are able localize the alarms. The fifth research question investigates subjects’ choice response time to the auditory and haptic alarm modes.

H5 - The Auditory Alarm Mode Will Yield Faster Choice Response Times than the Haptic Seat Alarm Mode

The findings do not support this research hypothesis. In actuality, the haptic alarm mode yields mean choice response times 0.29 seconds faster than the auditory alarm mode. Subjects’ mean choice response time to the auditory alarm mode was 2.257 seconds, while their mean choice response times to the haptic alarm mode was 1.967 seconds. A reason for this may relate back to the discriminability of the alarm modes. The auditory alarm mode’s poor ability to differentiate adjacent target locations may have made the decision to select a target location harder. Referring back to Abel and Banerjee’s (1997) application of signal detection theory towards target localization, subjects’ judgment between signal and noise target locations may have required greater attentional demands. The consumption of attentional demands at the response selection stage of the information processing model (Wickens and Hollands, 1999) may be the reason for the increase in choice response times. In contrast, the haptic alarm mode’s higher discriminability may have made the decision between signal and noise target location easier. The shorter choice response times observed may be because response selection to it does not require equivalent attentional demands.

The sixth research question investigates the addition of a non-directional auditory component to the haptic alarm mode.

H6 - The Combination of a Non-Directional Auditory Alarm with a Haptic Seat Alarm Mode Will Yield Faster Response Times than the Haptic Seat Alarm Mode on its Own

The sixth research hypothesis is not supported. There are no significant differences in choice response time between the haptic alarm mode and the non-directional auditory and haptic combination alarm mode. Subjects’ mean choice response time to the haptic alarm mode was 1.967 seconds, while their mean choice response time to the haptic and non-directional auditory combination alarm mode was 1.921 seconds. This research question was explored based on Haas and Casali’s (1993) findings that louder pulses yield greater perceived urgency and shorter detection times. It was hypothesized that the non-directional auditory alarm would raise subject’s perceived urgency of the alarm and reduce their response times. A reason why no significant differences were observed between the haptic alarm mode and the non-directional auditory and haptic combination alarm mode may be that subjects’ vigilance over the course of the experiment remained constant. Given that the on-road section of the experiment lasted two and a half hours, subject’s vigilance may not have diminished due to the alarms being played every minute. The choice response time to an alarm mode thus became dependant on how discriminable it was. Driver fatigue, however, may yield significant differences in choice response time between the haptic alarm mode and the non-directional auditory and haptic combination alarm mode.
The seventh research question hypothesizes the existence of age effects:

**H7 - Older Drivers will have Increased Response Times to Stimuli then Younger Drivers**

The last hypothesis is also not supported. There are no significant differences in mean choice response time between older and younger subjects (p = 0.4119). Younger subjects had a mean choice response time of 1.965 seconds, while older subjects had a mean choice response time of 2.099 seconds. The reader is reminded that an equal emphasis was placed on speed and accuracy when explaining the experiment to the subjects. Nevertheless, a reason why no significant differences were observed may be because older and younger subjects’ equally focused on responding quickly to the alarms. In doing so, the degradation in performance with age surfaced in their accuracy scores.

It is interesting to note that Tan and Lerner (1996) observed significant differences in the time taken to make course movement of the joystick in localizing auditory alarms between younger and older subjects. They reported that younger subjects responded with a mean response time of 0.95 s, while older subjects required about a half second longer. One reason why Tan and Lerner found significant differences in response time, while this study did not, may be owing to unequal emphasis subjects may have placed on responding accurately versus quickly between the two studies. Tan and Lerner instructed their subjects to “respond as quickly and as accurately as possible once they had determined the location of a sound.” Whereas, this study asked subjects to “quickly verbalize the location of the alarm using their terminology while being as correct as possible.” Perhaps the different instructions lead subjects to place unequal emphasis on responding accurately.

### 5.3. Which Alarm Modes Do Drivers Prefer?

The subject preferences discussed in this section were derived from hypothetical situations. Subjects’ preferences to the inquired situations may differ if the alarms are experienced under actual collision avoidance conditions.

In response to both the alarm mode directional questionnaire and alarm mode ranking questionnaire, subjects consistently prefer the three haptic alarm modes to the auditory alarm mode. Significant differences between the auditory and haptic combination alarm mode and the non-directional auditory and haptic combination alarm mode are not found. Subjects’ preferences towards the haptic alarm mode and the addition of the auditory alarm to the haptic alarm mode vary for certain hypothetical situations. These differences are discussed below.

Subjects feel that the addition of an auditory alarm to the haptic alarm mode is the “best method for presenting crash alerts to drivers,” the “most noticeable method in the car,” the “best method for getting (their) attention immediately if (they are) distracted,” and the “best method for telling (them) that (they) are in danger and need to react immediately.” Subjects believe that the addition of an auditory alarm to the haptic alarm mode holds the “greatest potential for presenting crash alert information (that prevents them) from getting in an accident,” and is the preferred method for allowing them to “respond quickly and appropriately to (a) crash threat.” Subjects commented that the haptic alarm mode helped them identify the target location, while the auditory alarm grabbed
their attention. These results suggest that the addition of the auditory alarm to the haptic alarm mode could yield a higher sense of perceived urgency, while maintaining the directional information clarity of the haptic alarm mode. If this is true, then the addition of the auditory alarm mode to the haptic alarm mode may be beneficial to distracted or fatigued drivers.

The alarm’s efficacy in grabbing and directing a driver’s attention is important when a potential crash situation is properly assessed by the collision avoidance system. However, a high rate of false alarms may incline designers to incorporate a collision avoidance alarm that minimizes inappropriate reactions and driver annoyance. Subjects feel that the haptic alarm mode on its own “startles them the least.” The heightened sense of being startled brought on by the auditory alarm mode may cause drivers to erroneously alter their driving behavior when it is unsubstantiated. The haptic alarm mode on its own may not affect drivers to the same degree. Subjects also feel that the haptic alarm mode is the least annoying given weekly and daily false alarms, and is the least annoying to their passengers. Drivers conscious of their passenger’s well-being may become distressed if they believe their vehicle is annoying their passengers. This distress may impose additional attentional demands on drivers, distracting them from the driving task. Driver annoyance should be carefully considered before implementing the collision avoidance alarms. Annoying alarms could have a reverse impact on collision avoidance system effectiveness.

Subjects equally believe that the haptic alarm mode and the addition of the auditory alarm to the haptic alarm mode “interfere the least with (their) ability to make quick and accurate decisions about the safest driving action to take,” “interfere the least with (their) ability to perform a quick and accurate emergency driving action,” and are the “best method(s) for presenting crash alert information that gets (their) attention without being overly annoying.” Subjects also equally believe that the haptic alarm mode and the addition of the auditory alarm to the haptic alarm mode are the “least out of place in a car or truck,” and the “least confused with events happening inside or outside the car.”

Given these results, it is possible that the haptic alarm mode on its own suffices as a collision avoidance alarm. Further testing of these alarm modes under actual collision avoidance conditions is needed to substantiate this claim.

5.4. General Discussion

Overall, subjects’ ability to accurately localize alarms is dependent on the alarm mode, target location, and their age. Under the conditions studied, the haptic alarm mode performs better than the auditory alarm mode in terms of accuracy. A reason why the auditory alarm mode performed poorly may be owing to the presence of sound reflections within the vehicle cabin as well as the perceptual reversals between the front and rear target locations. Upon closer inspection of subjects’ responses to the haptic alarm modes, the majority of errors were marginal. Haptic alarm mode localization errors such as directing drivers’ attention to the front vs. the front-right of the vehicle may be practically meaningless. An object, such as a car or truck, evoking the alarm may still be identifiable owing to its considerable size. However, clearer differentiation between adjacent target locations may further improve discriminability to the extent such an improvement is needed. Two ways in which this could be done are redesigning the placement of the target locations, and reducing
the number of target locations. Placing the target locations further away from each other may make them more discriminable. Following the same premise, reducing the number of target locations may allow the distance separating them to be increased. In the process of ensuring that the collision avoidance alarm effectively supports drivers, designers of collision avoidance systems should establish the locations around the vehicle that drivers may need to monitor in order to maintain spatial awareness of surrounding vehicles.

Even if the haptic alarm mode and auditory alarm mode are redesigned to be equivalently discriminable, certain considerations give the haptic alarm mode an advantage over the auditory alarm mode. The haptic alarm mode is not affected by the presence of acoustical noise from the windows being down or passenger discussion. In comparison, the presence of such noise detracts from the detectability of the auditory alarm mode. The presence of passengers and carry-on also changes the acoustical nature of the car cabin, which may affect the way in which the auditory alarm is perceived. The haptic alarm mode is devoid of this problem. Degradation in subjects’ hearing with age also may make the auditory alarm mode less effective than the haptic alarm mode for certain driving populations. Production of the alarms for variously sized vehicles requires the auditory alarm to be calibrated for each vehicle model’s cabin. The haptic alarm mode does not need to be calibrated since it is particular to the driver seat.

The hindering effects that the limitations of the auditory senses have on the effectiveness of a spatial audio display were pointed out. Following this premise, it is possible that subjects’ physical characteristics may affect how they perceive the haptic alarm mode. An investigation of the effects of subject anthropometry on haptic alarm mode localization accuracy was conducted. A stepwise multiple linear regression analysis was used to search for the optimum subset of variables that explained the percent correct response variable. The model parameters were height, weight, waist size, inseam length, femoral length, and the distance across thighs. The best-fit model only accounted for 21% of the haptic alarm accuracy score. The results suggest that subjects’ physical size does not affect their ability to accurately localize the haptic alarm mode.

Overall, subjects’ ability to localize auditory and haptic alarms in terms of response time is dependent on the alarm mode and the target location from which they are evoked. Under the conditions investigated, the haptic alarm mode performs significantly better than the auditory alarm mode. The choice response time to an alarm may be reduced if its discriminability is improved. A more discriminable alarm will impose less attentional demands in deciphering between adjacent target locations.

It should be noted that the choice response times obtained include the time the experimenter took to press a button once the subject began to verbally respond. As a result, actual mean choice response time is likely less than the mean 2.0 seconds measured in this study. Dufour and Peereman (2003) report that humans take under 0.3 seconds to respond to a verbal auditory signal. Assuming this is the mean time the experimenter took to press the button once the subjects responded, then an estimate of the actual choice response time can be attained by reducing the measured mean choice response times by this amount. However, it remains unclear the extent to which these choice response time levels are representative of those found under collision threat conditions which are likely to contain significant information regarding the probabilities associated with various possible directions of collision threat.
Response time and accuracy are two dimensions of information processing performance. Performance along these two dimensions is constrained by peoples’ information processing capabilities. Nevertheless, people are able to trade off performance between these two dimensions. In general, when people focus on speed, their accuracy degrades and becomes a chance event. When people focus on accuracy, their response time is extended. Closer inspection of the collected data revealed that the differences in mean choice response time and accuracy between the auditory alarm mode and the haptic alarm modes were not due to speed-accuracy tradeoffs. From the speed-accuracy graphs previously shown in figure 38, the upper left location of the haptic alarm mode plots relative to the lower right location of the auditory alarm mode plots suggests that there is an increase in information processing effectiveness or efficiency in switching from the auditory alarm mode to the haptic alarm modes (Wickens and Hollands, 1999).

Conclusions

Under the conditions investigated, this study showed that subjects localize the haptic alarm mode faster and more accurately than the auditory alarm mode while driving a vehicle at 55 mph. Subjects performed equally well with the haptic alarm mode, the auditory and haptic combination alarm mode, and the non-directional auditory and haptic combination alarm mode in terms of speed and accuracy in identifying their location. Subjects’ preferred the addition of the auditory component to the haptic alarm mode for hypothetical situations of driver distraction, perhaps owing to the heightened sense of urgency it provides. However, subjects preferred the haptic alarm mode on its own given hypothetical false alarms, perhaps because it was less annoying. Subjects felt that the haptic alarm mode and auditory and haptic alarm modes equally interfered with their ability to make hypothetical quick and accurate emergency driving action. A reason why subjects’ performance differed between the alarm modes is explained using signal detection theory and was integrated into a model of human information processing. Alarm mode discriminability was believed to affect localization accuracy and response time owing to its effect on the likelihood of correctly identifying a target location and the attention resources required to differentiate adjacent target locations. Based on the conditions investigated, it is possible that the haptic alarm mode suffices as a collision avoidance alarm.
Implications of Research

Designers of integrated collision avoidance alarms can learn the following principles from this research:

1) CAS alarms intended to identify different locations must be clearly differentiable from one another in order to optimize quick response times and accuracy.

2) The haptic alarm mode may be more effective at quickly and accurately indicating a direction to a driver than the auditory alarm mode.

3) The haptic alarm mode performs equally as good as the haptic and auditory combination alarm modes in terms of response time and accuracy.

Consideration for these inferences will assist in the design of effective collision avoidance alarms that account for drivers’ capabilities and limitations.

Generalizability of the Research

This research was intended to be generalizable to the driving population. Subjects performed the localization task while driving on an open road at 55 mph. As a result, subjects were forced to divide their attention between the localization task and driving task just as they would in a real-life situation. Subjects were exposed to a realistic representation of the road noise, consisting of both sound and vibration, which masked the CAS alarms. Subjects were balanced across gender in order to avoid gender biases in the results. The experiment was also carried out during the winter months. Since subjects were dressed in thicker clothing when perceiving the haptic alarm, the results are generalizable to the summer months when subject’s attire is not as heavy.

The study faces the following limitations. The choice response times were measured by the experimenter pressing a button after subjects verbally responded. As a result, the response time measurements include additional variation from the experimenter reacting to the subjects’ voice, and are thus not entirely accurate. The alarms were evoked consistently every minute. As a result, subjects’ expectancy towards the alarms did not change and may have affected their response time. The alarms were also presented from each target location with equal probability. In reality, the likelihood of encountering a collision from various directions may differ. Information theory suggests that the differences in likelihood between each target location of an alarm sounding may affect drivers’ response times to it (Hyman, 1953). Alarms evoked from rarer target locations could be reacted to more slowly than common target locations.

The spatial auditory display consisted of the test vehicle’s stock sound system. A reason why the auditory alarm mode performed poorly may be that the position of the speakers did not map as well as the haptic actuators did to the eight target locations. Different speaker arrangements may yield different localization performance. Subjects were only exposed to road noise. Noise resulting from the windows being down and verbal discussions amongst passengers may affect the detectability of the auditory alarm mode. It should be noted that the haptic alarm mode performance should
theoretically not be affected. The alarms were not presented while the vehicle traveled over bridges and through turns. The increase in both auditory and vibration road noise from driving over a bridge may detract from the alarms’ ability to be perceived. Additionally, since people rotate their heads when making turns, localization accuracy of the auditory alarm mode may be affected during such situations.

The study did not provide a collision avoidance context to the drivers. The performance of the alarms in actual collision situations, or in the presence of passengers, may differ from the collected data.

**Future Research**

Future research on drivers’ ability to localize auditory and haptic alarms in terms of response time and accuracy should expand beyond the limitations listed in the previous section. An investigation of driver reaction time, by measuring the time taken for drivers’ eyes to glance at the target locations, could provide a more accurate representation of the alarm modes’ ability to quickly direct drivers’ attention. Future research should employ an element of surprise to test reaction times to unknown events. This could be done by varying the times at which the alarms are presented, or by using an actual object as a surprise condition in the experiment. Utilizing actual obstacles would also augment the level of reality, increasing the study’s generalizability. For studies that focus on the localization of auditory alarms inside vehicles, consideration for the alarms frequency and format should be taken. It is believed that localization using the precedence effect can be optimized if the alarm contains broad spectral frequencies, and consist of impulse clicks. The arrangement of the speakers is important to consider. The use of direct sound, as opposed to summing localization, is worth investigating. Perhaps a speaker arrangement proximally centered on the driver’s head may assuage the obstruction of sound from the vehicle cabin components. The number of speakers to utilize must also be considered. Designers must ensure that the collision avoidance system supports the driving task by providing needed location information to the driver. Once this is done, an investigation of the minimal amount of speakers should be conducted. Wallace and Fisher (1998) used information theory to suggest that fewer speakers transmit more information to drivers, and are responded to faster. Fewer target locations could be spaced further apart, and thus become more discriminable. Accordingly, presenting four target locations as opposed to eight may yield a decrease in response time. Future localization studies should also include a measure of target location discrepancy in order to help explain differences in localization performance. The inclusion of driver fatigue and distraction would improve the face value of localization studies. Consideration for these factors may contribute to the design of more effective collision avoidance alarms.
Glossary of Terms

**Pure Tone**: A sound occurring at one frequency.

**Broadband Sound**: A sound comprising of multiple frequencies, both high and low, across the frequency spectrum.

**White noise**: A sound containing every frequency within the range of human hearing (generally from 20 hertz to 20 kHz) in equal amounts.

**Pink noise**: A variant of white noise. Pink noise is white noise that has been filtered to reduce the volume at each octave.

**1/3 octave**: Humans are capable of hearing sounds between 20 Hz and 20 kHz. Since the sounds we hear comprise of various frequencies, the audible frequency range is divided into 24 frequency bands known as 1/3 octave bands. A sound can be represented as the combination of sound pressure levels at each band.

**dBA**: The standard measure of sound pressure level since it approximates the sensitivity of the human ear at moderate sound levels by applying a weight to the sound pressure levels of each 1/3 octave band.

**dBC**: A weighted sound pressure level used to evaluate sounds whose low-frequency components are responsible for secondary effects such as vibration.

**Haptic**: of, or relating to the sense of touch.

**Localization**: The law or rule by which the location of an event (e.g., its direction or distance) is related to a specific attribute or attributes of the event, or of another event that is in some way correlated with the event.”

**Azimuth**: The horizontal angular distance from a reference direction.

**Anechoic**: Neither having nor producing echoes.

**Reverberant Chamber**: Having a tendency to reverberate or be repeatedly reflected.

**Precedence Effect**: States that the localization cues from the direct sound dominate those perceived from the reflections since it is heard first

**Sound Click (Impulse)**: The shortest possible sound (a single pressure spike). It contains the broadest possible frequency profile. It resembles a hand clap but is even shorter in duration.

**Summing localization**: The perceptual integration of two separate sounds in space.
References


Appendix A: IRB Protocol

Title: EVALUATION OF DRIVERS’ ABILITY TO LOCALIZE AUDITORY AND HAPTIC CUES

Submitted by: Greg Fitch, Shane McLaughlin and Jon Hankey

JUSTIFICATION OF RESEARCH PROJECT

The purpose of this research is to investigate drivers’ ability to localize the direction of auditory and vibrotactile (haptic) cues in a naturalistic driving environment. This research is initiated in response to the development of multidirectional sensors that detect potential on-road threats surrounding the vehicle. Results from this study will contribute to a recommended integrated crash alert system approach that directs drivers’ attention to the location of the on-road threats. Through a controlled study, participants’ use of a collision avoidance/Buick LeSabre vehicle will provide generic data on how to design these systems in the future. The study will provide an understanding and guidance related to peoples’ ability to localize sound and haptic cues while driving as well as preferences for cue presentation.

Contribution of Research Findings

Findings of this research will directly contribute to the design of Integrated Collision Avoidance Systems (ICAS). The information gathered will provide insight on whether people can localize sounds while dealing with the distractions associated with driving a vehicle. Also, by understanding the capabilities of users, a system can be designed to complement a user’s needs. Findings will reveal whether ICAS systems augment the driver’s ability to localize on-road threats surrounding their vehicle. Driver’s preferences with regard to the auditory and haptic cues will also be assessed.

Use of the multidirectional sensors could potentially assist the driver by providing earlier alert of objects or slow moving vehicles in the path of travel. This type of system can increase the available response time for drivers and provide an alternative warning mode (e.g., auditory or haptic) of hazards. All of these benefits can potentially make driving in traffic less demanding, more convenient, and safer for the driver. On a larger scale, ICAS systems contribute to the overall safety of automotive transportation by assisting drivers in developing spatial awareness, thereby providing benefit to individual users as well as the broader population. Greater understanding of the behavior and needs of a driver working with an ICAS system will contribute to the evolution of future more comprehensive intelligent vehicle systems. The outcome of this investigation may have a significant impact on driving safety, system usability, traffic flow, consumer satisfaction, and design of future automated systems.
EXPERIMENTAL PROCEDURES

Participant Population

The subject pool will consist of 32 participants, equally divided between two age groups. The younger age group will be drivers between the ages of 20 and 30 years old. The older age group will be drivers between the ages of 60 and 70 years old. Both male and female subjects will be recruited equally. Prior to coming in for testing, a general description of the study requirements will be provided. Participants will be informed that the study requires them to report their height, weight, inseam length, femoral length, and distance across their thighs. Participants for this experiment will be recruited through the Virginia Polytechnic Institute and State University, local retirement communities, and contacts made through word of mouth. Participants will be screened initially with a verbal questionnaire to determine if they are licensed drivers and if they have any health concerns that should exclude them from participating in the study. The attached Screening Questionnaire is based on the standard questionnaire used by the Virginia Tech Transportation Institute to screen participants (see Attachment 1). Specific questions regarding hearing deficits have been added.

Participants will be paid $20 per hour. If the participant chooses to withdraw, he or she will be compensated for the portion of time of the study for which he or she participated.

Experimental Tasks

The experiment will require participants to come in for one session, and will include approximately three hours of driving. Participants will be met at the Virginia Tech Transportation Institute and given a brief overview of the study. They will be asked to produce a valid driver’s license and then to read over the informed consent form (see Attachment 2). An experimenter will be present to answer any questions the participant may have. If participants agree with the informed consent, they will be asked to sign and date it. Participants will be given a copy of the informed consent to keep. The participants’ vision will be screened using a simple acuity test. Participants must have 20/40 vision or better to continue on with the study. Participants’ hearing will be tested using an Earscan Microprocessor Pure Tone Audiometer which involves the participant wearing earphones which are similar to those used with home audio systems. Participants will be required to have uncorrected hearing levels of less than or equal to 40dB at 500Hz, 1000Hz, 2000Hz, 3000Hz, and 4000Hz without bilateral hearing differences of more than 10dB. Participants who do not meet the vision and hearing criteria will be thanked for their time, paid $20.00 and dismissed.

The experimenter will provide the participant with a brief overview, explaining what an Integrated Collision Avoidance System is and how it works. The experimenter will then orient the participant to the vehicle. The participant will be briefed on operation of the 3D auditory cues generated throughout the vehicle’s cabin, and the haptic cues generated from the driver’s seat. The experimenter will clarify that the ICAS in the test vehicle is only a simulation, and the vehicle is not equipped with any external sensors to detect objects outside the vehicle. Therefore, the tones and seat vibrations they experience during the study are not the result of external traffic or objects.
When all the participant’s questions have been answered the experimenter will instruct him/her to drive the vehicle to the predetermined test route. The test route will consist of rural roads, main arterials, and side streets in the New River Valley. The experimenter will remain in the vehicle and monitor the participant’s driving throughout the study. Throughout the drive, the driver will be presented with audio cues in various locations throughout the cab and haptic cues in various locations on the driver’s seat. The participant will be instructed to notify the experimenter when they detect the cues, and of the location they believe the cue was alerting them to. The experimenter will not present an audio or haptic cue when the external environment requires increased driver attention.

Upon completion of the test route, the experimenter will instruct the participant to drive the vehicle back to VTTI. A post drive questionnaire will be administered (Attachment 3).

Participants will be paid at the rate of $20.00 per hour. If at any time the participant chooses to stop, he/she will be paid for the portion of time in which he/she participated. After the completion of the experimental session, the participant will be paid for his or her time, thanked, and dismissed.

All data collection will take place during daylight hours. In the event of severe weather, data collection will be cancelled

RISKS AND BENEFITS

There are risks or discomforts to which test participants are exposed in volunteering for this research. They include the following:

1) The risk of an accident normally present while driving an unfamiliar vehicle.
2) Possible fatigue during longer driving segments. However he/she may take breaks if necessary.
3) Participants who have had previous eye injuries are at an increased risk of further eye injury by participating in a study where risks, although minimal, include the possibility of collision and airbag deployment.

The following precautions will be taken to ensure minimal risk to the participants.

1) An experimenter will monitor the participant’s driving and will ask the participant to stop if he or she feels the risks are too great to continue.
2) Participants will be encouraged to take breaks if they desire.
3) The experimenter will be present while the participant is driving. However, as long as the participant is driving the research vehicle, it remains his or her responsibility to drive in a safe, legal manner.
4) Participants will be required to wear the lap and shoulder belt restraint system while in the car. The vehicle is equipped with a driver's side and passenger's side airbag supplemental restraint system, fire extinguisher and first-aid kit.
5) If an accident does occur, the experimenter will arrange medical transportation to a nearby hospital emergency room. Participants will be required to undergo examination by medical personnel in the emergency room.

6) All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to the driver in any foreseeable case.

7) Participants who are pregnant will be required to indicate they have reviewed the Informed Consent Form with their obstetrician and discussed the risks of participating in the study with him or her.

There are no direct benefits to the participant beyond potentially finding the experiment interesting. No promise or guarantee of benefits will be made to encourage subjects to participate. Subject participation may have significant impact on driving safety, system usability, traffic flow, consumer satisfaction, and design of future collision avoidance systems.

CONFIDENTIALITY / ANONYMITY

The data gathered in this experiment will be treated with confidentiality, and data collected will be used for research purposes only. Shortly after participants have participated, their name will be separated from their data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 3). Participants will be allowed to see their data and withdraw them from the study if they so desire. Participants must inform the experimenter immediately of this decision, as the data will be difficult (if not impossible) to track once the session is over.

While the participant is driving the vehicle, a camera will record him/her. A small camera, positioned near the center rear-view mirror, is used to record drivers' behavior. The digital image recorded is of the driver's head with some additional space around the head to accommodate any head-movements by the driver during data collection.

The digital images will be kept on a password-protected server with access granted only to individuals working on the project. Access to the images will be under the supervision of Greg Fitch, the principal investigator for the project.
Appendix B: Driver Screening and Demographic Questionnaire

Note to Researcher:
Initial contact between participants and researchers may take place over the phone. If this is the case, read the following Introductory Statement, followed by the questionnaire. Regardless of how contact is made, this questionnaire must be administered verbally before a decision is made regarding suitability for this study.

Introductory Statement:
After prospective participant calls or you call them, use the following script as a guideline in the screening interview.
Hello. My name is _____ and I'm a researcher with the Virginia Tech Transportation Institute in Blacksburg, VA. We are currently recruiting people to participate in a research study. This study will require one or two sessions. The first session lasts about twenty minutes and consists of a simple hearing test. For individuals who meet hearing requirements, a second session will be scheduled. The second session lasts about three hours, during which participants will drive a vehicle equipped with data collection equipment on highways in Blacksburg. We will request that you provide us with your weight, waist size, and inseam length and we will make a measurement of the distance across your legs while you are in the vehicle. This information will help us understand what portions of the driver’s seat you contact while driving. After the drive you will respond to some questionnaires about the systems. Participants will be paid $20.00 per hour at the end of the session. Does this sound like something you’d like to participate in?

Next, I would like to ask you several questions to see if you are eligible to participate.

1. Do you have a valid driver's license?
   - Yes
   - No

2. How old are you? _______________ (Stop if not 20-30 or 60-70)

3. How long have you held your driver's license? _______________

4. Are you able to drive an automatic transmission without assistive devices or special equipment?
   - Yes
   - No

5. Have you had any moving violations in the past 3 years? If so, please explain.
   - Yes ____________________________
   - No
6. Have you been involved in any accidents within the past 3 years? If so, please explain.
   - Yes ______________________________________________________
   - No

7. Do you have a history of any of the following? If yes, please explain.
   - Heart Condition   No____ Yes________________________________
   - Stroke            No____ Yes________________________________
   - Brain tumor       No____ Yes________________________________
   - Head injury       No____ Yes________________________________
   - Epileptic seizures No____ Yes________________________________
   - Respiratory disorders No____ Yes________________________________
   - Motion sickness   No____ Yes________________________________
   - Inner ear problems No____ Yes________________________________
   - Dizziness, vertigo, or other balance problems
     No____ Yes________________________________
   - Diabetes          No____ Yes________________________________
   - Migraine, tension headaches
     No____ Yes________________________________

8. (Females only) Are you currently pregnant?
   - Yes _____
   - No _____
   (If “yes” then read the following statement to the subject: “It is not recommended that pregnant women participate in this study. However, female subjects who are pregnant and wish to participate must first consult with their personal physician for advice and guidance regarding participation in a study where risks, although minimal, include the possibility of collision and airbag deployment.”)

9. Are you currently taking any medications on a regular basis? If yes, please list them.
   - Yes ______________________________________________________
   - No

10. Do you have normal or corrected to normal vision? If no, please explain.
    - Yes
    - No ______________________________________________________

11. Do you wear a hearing aid?
    - Yes
    - No

12. Do you have any hearing disabilities, such as Tinnitus? If Yes, please explain.
    - Yes ______________________________________________________
    - No
13. Do you have any neuro-motor impairment or trouble feeling in your legs? If yes, please explain.
   - Yes ______________________________________________________
   - No

14. How often do you drive each week (counting each trip as a separate occasion)?
   - Less than 2 times per week
   - 2 to 4 times per week
   - More than 4 times per week

Criteria For Participation:

1. Must have a valid driver's license for the last two years.
2. Must be 20-30 or 60-70 years of age.
3. Must drive at least 2 times a week.
4. Must have normal vision.
5. Must not have any hearing deficits (corrected or otherwise).
6. Must be able to drive an automatic transmission without special equipment.
7. Must not have more than two driving violations in the past three years.
8. Must not have caused an injurious accident in the past two years.
9. Cannot have history of heart condition, lingering effects of brain damage from stroke, tumor, head injury, recent concussion, or infection. Cannot have had epileptic seizures within 12 months, respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.
10. Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities).
11. Cannot be pregnant
12. Must have normal or corrected vision
13. Must not wear a hearing aid
14. Must not have any hearing disabilities
15. Must not have any neuromotor impairment or trouble feeling in the legs

For those who meet the above requirements:
Schedule their hearing time. Then explain,

Okay, I have you scheduled for the first session on _____________ at _____________ . If you meet the study’s hearing requirements, we will schedule you for a second session at that time.
Appendix C: Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants of Investigative Projects

Title of Project: Using Tones and Haptic Cues to Determine Locations

Investigators: Greg Fitch, Shane McLaughlin, and Jon Hankey

I. The Purpose of this Research/Project

The purpose of this study is to investigate the use of auditory tones and seat vibration to notify drivers of the direction of a potential collision situation. For example, a tone could sound to indicate a stopped lead vehicle in the driver’s path. The results of this study will contribute to the design and usability of future collision avoidance systems.

II. Procedures

1. Read and sign this Informed Consent Form (if you agree to participate).
2. Show a current valid driver’s license.
3. Complete questionnaires
4. Drive an instrumented vehicle on a predetermined route in the New River Valley and notify the experimenter when you can detect the driver’s seat vibrating, and when you can detect specific audio tones. It is important to note that the tones and vibrations you will experience while driving are intended to simulate warnings that an integrated collision avoidance system might produce. The vehicle is not equipped with a working collision avoidance system, and therefore, will not warn you of possible collisions.

III. Risks

The scenarios examined in this study will involve responding to auditory tones and seat vibrations while driving on the road in normal traffic. At various times, system generated alert tones and seat vibration indicators may occur. The use and function of this system will be new to you. Caution should be exercised when operating equipment with which you are not familiar. Be aware that accidents can happen at any time while driving.

There are risks or discomforts to which test participants are exposed in volunteering for this research. They include the following:

1) The risk of an accident normally present while driving an unfamiliar vehicle.
2) Possible fatigue due to length of driving segment.
3) If you have had previous eye injuries you are at an increased risk of further eye injury by participating in a study where risks, although minimal, include the possibility of collision and airbag deployment.

The following precautions will be taken to ensure minimal risk to you:

1) An experimenter will monitor your driving and will ask you to stop if he or she feels the risks are too great to continue. However, as long as you are driving the research vehicle, it remains your responsibility to drive in a safe, legal manner.
2) You may take breaks if you desire.
3) You are required to wear the lap and shoulder belt restraint system while in the car.
4) The vehicle is equipped with a driver's side and passenger's side airbag supplemental restraint system, fire extinguisher and first-aid kit.
5) If you are pregnant you will be required to indicate you have reviewed the Informed Consent Form with your obstetrician and discussed the risks of participating in the study with him or her. You are willing to accept all possible risks of participation.
6) If an accident does occur, the experimenters will arrange medical transportation to a nearby hospital emergency room. Participants will be required to undergo examination by medical personnel in the emergency room.
7) All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to the driver in any foreseeable case.
8) None of the data collection equipment or the display technology interferes with any part of the driver’s normal field of view present in the automobile.
9) You do not have any medical condition that would put you at a greater risk, including but not restricted to epilepsy, balance disorders, and lingering effects of head injuries or stroke.

In the event of an accident or injury in an automobile, the automobile liability coverage for property damage and personal injury is provided. The total policy amount per occurrence is $2,000,000. This coverage (unless the other party was at fault, which would mean all expense would go to the insurer of the other party’s vehicle) would apply in case of an accident for all volunteers and would cover medical expenses up to the policy limit.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation; under Commonwealth of Virginia law, workers compensation does not apply to volunteers; therefore, if not in an automobile, the participants are responsible for their own medical insurance for bodily injury. Appropriate health insurance is strongly recommended to cover these types of expenses.

IV. Benefits of this Project

While there are no direct benefits to you from this research, you may find the experiment interesting. No promise or guarantee of benefits is made to encourage you to participate. Participation in this study will contribute to the development of collision avoidance systems. Improvements in the design of this type of system may have a significant impact on driving safety, system usability, and consumer satisfaction.

V. Extent of Anonymity and Confidentiality

The data gathered in this experiment will be treated with confidentiality. Shortly after participation, your name will be separated from your data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 1). You will be allowed to see your data and withdraw the data from the study if you so desire, but you must inform the experimenters immediately of this decision so that the data may be promptly removed. A camera will be used to record data during the study. These digital images will only be accessed by staff working on this project.
VI. Compensation

You will be paid $20.00 per hour for participating. You will be paid at the end of this study in cash.

Freedom to Withdraw

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty.

VIII. Approval of Research

Before data can be collected, the research must be approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Virginia Tech Transportation Institute. You should know that this approval has been obtained.

Subject’s Responsibilities

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To follow the experimental procedures as well as you can.
2. To inform the experimenter if you incur difficulties of any type.
3. Wear your seat and lap belt.
4. Abide by the posted speed limits and traffic laws.
5. To abstain from any substances that will impair your ability to drive.
X  Participant’s Permission

Check one of the following:

☐ I have not had an eye injury/eye surgery (including, but not limited to, LASIK, Radial Keratotomy, and cataract surgery.)

☐ I have had an eye injury/eye surgery and I’ve have been informed of the possible risks to participants who have had eye surgery. I choose to accept this possible risk to participate in this study.

XI  Subject’s Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Signature          Date

Should I have any questions about this research or its conduct, I may contact:
Greg Fitch        231-1500
Shane McLaughlin     231-1500
David Moore (Institutional Review Board Chair) 231-4991
Appendix D: Post Drive Questionnaires
**Directional Tone Alert Appropriateness**

Assume that the crash alerts you just experienced are going to be implemented in a vehicle. Use the rating scale below to respond to each question about the warning. Mark the number from the scale that corresponds to your response in the space provided at the beginning of each question. Please pick an exact number. Fractions (such as 3.5) are not permitted.

How would you rate the **loudness** of this warning? ______

![Rating Scale for Loudness](chart)

How would you rate the **duration** or length of this warning? ______

![Rating Scale for Duration](chart)
Directional Tone Directional Information
Please indicate the extent to which you agree with the following statements. Use the numbering on the scale above to make your responses. Place your response in the appropriate column below. Please pick an exact number. Fractions (such as 3.5) are not permitted.

<table>
<thead>
<tr>
<th></th>
<th>1. Overall, this is a good method for allowing the driver to quickly determine the direction of the crash threat</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2. Overall, this is a good method for allowing the driver to quickly distinguish between threats on the front-left versus those on the rear-left</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Overall, this is a good method for allowing the driver to distinguish between threats on the front versus those on the front-left</td>
<td></td>
</tr>
</tbody>
</table>
4. Overall, this is a good method for allowing the driver to distinguish between threats **on the front versus those on the front-right**

5. Overall, this is a good method for allowing the driver to distinguish between threats **on the front-left versus those on the left.**

6. Overall, this is a good method for allowing the driver to distinguish between threats **on the front-right versus those on the right.**
7. Overall, this is a good method for allowing the driver to quickly distinguish between threats on the rear versus those on the rear-left.

8. Overall, this is a good method for allowing the driver to quickly distinguish between threats on the rear versus those on the rear-right.

9. Overall, this is a good method for allowing the driver to distinguish between threats on the left versus those on the rear-left.
10. Overall, this is a good method for allowing the driver to distinguish between threats on the right versus those on the rear-right.
Directional Tone Comments

Please comment on this alarm. What did you like about it? What did you not like about it? Is there anything you would like to say that could make this alarm better?
**Seat Vibration Alert Appropriateness**

Assume that the crash alerts you just experienced are going to be implemented in a vehicle. Use the rating scale below to respond to each question about the warning. Mark the number from the scale that corresponds to your response in the space provided at the beginning of each question. Please pick an exact number. Fractions (such as 3.5) are not permitted.

How would you rate the **Intensity** of this warning? ______

![Intensity Scale]

How would you rate the **duration** or length of this warning? ______

![Duration Scale]
**Seat Vibration Directional Information**

Please indicate the extent to which you agree with the following statements. Use the numbering on the scale above to make your responses. Place your response in the appropriate column below. Please pick an exact number. Fractions (such as 3.5) are not permitted.

<table>
<thead>
<tr>
<th></th>
<th>Statement</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overall, this is a good method for allowing the driver to quickly determine the direction of the crash threat</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Overall, this is a good method for allowing the driver to quickly distinguish between threats <strong>on the front-left versus those on the rear-left</strong></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Overall, this is a good method for allowing the driver to distinguish between threats <strong>on the front versus those on the front-left</strong></td>
<td></td>
</tr>
</tbody>
</table>
4. Overall, this is a good method for allowing the driver to distinguish between threats on the front versus those on the front-right.

5. Overall, this is a good method for allowing the driver to distinguish between threats on the front-left versus those on the left.

6. Overall, this is a good method for allowing the driver to distinguish between threats on the front-right versus those on the right.
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Strongly Disagree</td>
<td>Moderately Disagree</td>
<td>Perhaps Disagree</td>
<td>Neutral</td>
<td>Perhaps Agree</td>
<td>Moderately Agree</td>
<td>Strongly Agree</td>
<td></td>
</tr>
</tbody>
</table>

7. Overall, this is a good method for allowing the driver to quickly distinguish between threats **on the rear versus those on the rear-left**.

8. Overall, this is a good method for allowing the driver to quickly distinguish between threats **on the rear versus those on the rear-right**.

9. Overall, this is a good method for allowing the driver to distinguish between threats **on the left versus those on the rear-left**.
10. Overall, this is a good method for allowing the driver to distinguish between threats **on the right versus those on the rear-right**
Seat Vibration Comments
Please comment on this alarm. What did you like about it? What did you not like about it? Is there anything you would like to say that could make this alarm better?
Directional Tone Alert Appropriateness

Assume that the crash alerts you just experienced are going to be implemented in a vehicle. Use the rating scale below to respond to each question about the warning. Mark the number from the scale that corresponds to your response in the space provided at the beginning of each question. Please pick an exact number. Fractions (such as 3.5) are not permitted.

How would you rate the loudness of this warning? ______

[Rating Scale]

1  2  3  4  5  6  7
Extremely Soft Moderately Soft Slightly Soft Just Right Slightly Loud Moderately Loud Extremely Loud

How would you rate the duration or length of this warning? ______

[Rating Scale]

1  2  3  4  5  6  7
Extremely Short Moderately Short Slightly Short Just Right Slightly Long Moderately Long Extremely Long
Seat Vibration Alert Appropriateness

Assume that the crash alerts you just experienced are going to be implemented in a vehicle. Use the rating scale below to respond to each question about the warning. Mark the number from the scale that corresponds to your response in the space provided at the beginning of each question. Please pick an exact number. Fractions (such as 3.5) are not permitted.

How would you rate the intensity of this warning? ______

How would you rate the duration or length of this warning? ______

Please indicate which one of the following statements you experienced (Please select only one)

_____ The tone alert was presented slightly before the seat vibration alert
_____ The seat vibration alert was presented slightly before the tone alert
_____ The tone alert and seat vibration alert were presented at the same time
### Directional Tone + Seat Vibration Directional Information

Please indicate the extent to which you agree with the following statements. Use the numbering on the scale above to make your responses. Place your response in the appropriate column below. Please pick an exact number. Fractions (such as 3.5) are not permitted.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, this is a good method for allowing the driver to quickly determine the direction of the crash threat</td>
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</tr>
<tr>
<td>2. Overall, this is a good method for allowing the driver to quickly distinguish between threats on the front-left versus those on the rear-left</td>
<td></td>
</tr>
<tr>
<td>3. Overall, this is a good method for allowing the driver to distinguish between threats on the front versus those on the front-left</td>
<td></td>
</tr>
</tbody>
</table>
4. Overall, this is a good method for allowing the driver to distinguish between threats **on the front versus those on the front-right**.

5. Overall, this is a good method for allowing the driver to distinguish between threats **on the front-left versus those on the left**.

6. Overall, this is a good method for allowing the driver to distinguish between threats **on the front-right versus those on the right**.
7. Overall, this is a good method for allowing the driver to quickly distinguish between threats **on the rear versus those on the rear-left**.

8. Overall, this is a good method for allowing the driver to quickly distinguish between threats **on the rear versus those on the rear-right**

9. Overall, this is a good method for allowing the driver to distinguish between threats **on the left versus those on the rear-left**
10. Overall, this is a good method for allowing the driver to distinguish between threats **on the right versus those on the rear-right**.
**Directional Tone + Seat Vibration Comments**

Please comment on this alarm. What did you like about it? What did you not like about it? Is there anything you would like to say that could make this alarm better?
**Front Tone Only Alert Appropriateness**

Assume that the crash alerts you just experienced are going to be implemented in a vehicle. Use the rating scale below to respond to each question about the warning. Mark the number from the scale that corresponds to your response in the space provided at the beginning of each question. Please pick an exact number. Fractions (such as 3.5) are not permitted.

How would you rate the **loudness** of this warning? ______

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Soft</td>
<td>Moderately Soft</td>
<td>Slightly Soft</td>
<td>Just Right</td>
<td>Slightly Loud</td>
<td>Moderately Loud</td>
<td>Extremely Loud</td>
</tr>
</tbody>
</table>

How would you rate the **duration** or length of this warning? ______

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Short</td>
<td>Moderately Short</td>
<td>Slightly Short</td>
<td>Just Right</td>
<td>Slightly Long</td>
<td>Moderately Long</td>
<td>Extremely Long</td>
</tr>
</tbody>
</table>
Assume that the crash alerts you just experienced are going to be implemented in a vehicle. Use the rating scale below to respond to each question about the warning. Mark the number from the scale that corresponds to your response in the space provided at the beginning of each question. Please pick an exact number. Fractions (such as 3.5) are not permitted.

How would you rate the intensity of this warning? _______

How would you rate the duration or length of this warning? _______

Please indicate which one of the following statements you experienced (Please select only one)

- The tone alert was presented slightly before the seat vibration alert
- The seat vibration alert was presented slightly before the tone alert
- The tone alert and seat vibration alert were presented at the same time
Front Tone Only + Seat Vibration Directional Information

Please indicate the extent to which you agree with the following statements. Use the numbering on the scale above to make your responses. Place your response in the appropriate column below. Please pick an exact number. Fractions (such as 3.5) are not permitted.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, this is a good method for allowing the driver to quickly determine the direction of the crash threat</td>
<td></td>
</tr>
<tr>
<td>2. Overall, this is a good method for allowing the driver to quickly distinguish between threats on the front-left versus those on the rear-left</td>
<td></td>
</tr>
<tr>
<td>3. Overall, this is a good method for allowing the driver to distinguish between threats on the front versus those on the front-left</td>
<td></td>
</tr>
</tbody>
</table>
4. Overall, this is a good method for allowing the driver to distinguish between threats **on the front versus those on the front-right**

5. Overall, this is a good method for allowing the driver to distinguish between threats **on the front-left versus those on the left**.

6. Overall, this is a good method for allowing the driver to distinguish between threats **on the front-right versus those on the right**.
7. Overall, this is a good method for allowing the driver to quickly distinguish between threats **on the rear versus those on the rear-left**.

8. Overall, this is a good method for allowing the driver to quickly distinguish between threats **on the rear versus those on the rear-right**.

9. Overall, this is a good method for allowing the driver to distinguish between threats **on the left versus those on the rear-left**.
10. Overall, this is a good method for allowing the driver to distinguish between threats on the right versus those on the rear-right.
**Front Tone Only + Seat Vibration Comments**

Please comment on this alarm. What did you like about it? What did you not like about it? Is there anything you would like to say that could make this alarm better?
**Alarm Ranking**

This part of the questionnaire is unrelated to the rating scales previously used. Please **compare** each of the alarms by ranking them from 1 to 4, where 1 is best and 4 is worst, for the following statements. Please note that the numbers 1, 2, 3, and 4 can only be assigned **ONCE** per row.

<table>
<thead>
<tr>
<th></th>
<th>Directional Tone</th>
<th>Seat</th>
<th>Directional Tone + Seat</th>
<th>Front Tone Only + Seat</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>The best method for presenting crash alerts to drivers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b.</td>
<td>The most noticeable method in the car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c.</td>
<td>The method that is least confused with other events happening either inside or outside the car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d.</td>
<td>The best method for getting my attention immediately if I was distracted and not concentrating on the driving task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.</td>
<td>The method that startles me the least, that is, cause me to blink, jump, or make a rapid reflex-like movement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f.</td>
<td>The method that interferes the least with my ability to make a quick and accurate decision about the safest driving action to take (brake, steer, brake and steer, do nothing)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g.</td>
<td>The method that interferes the least with my ability to perform a quick an accurate emergency driving action</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h.</td>
<td>The method that least annoys me if the alert came on once a week in a situation where no driving action was required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>The method that least annoys me if the alert came on once a day in a situation where no driving action was required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j.</td>
<td>The method that least annoys my passengers if the alert came on where no driving action was required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>k.</td>
<td>The method that appears the least out of place in a car or truck</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l.</td>
<td>The best method for telling me that I am in danger and need to react immediately</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m.</td>
<td>The method that has the greatest potential for presenting crash alert information for preventing me from getting in an accident</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n.</td>
<td>The best method for presenting crash alert information that gets my attention without being overly annoying</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>o.</td>
<td>If your vehicle could warn you of any crash threat surrounding your vehicle, which method would you prefer to have so that you can respond quickly and appropriately to the crash threat</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix E: SAS Code Utilized

1. SAS Code Used to Analyze Response Time

```sas
libname ICAR 'C:\Documents and Settings\gfitch\My Documents\Data';
options nodate pageno=1;

/*Rearrangement of Data from Longitudinal to Columns in order to run GLM Repeated Measures Procedure*/
data icar.consult;
set icar.impdata;
RT = Reaction_Time__ms_; 
run;

proc sort data=icar.consult;
   by ID Location Alarm;
run;

proc univariate data=icar.consult noprint;
   var RT;
   by ID Location Alarm Gender Age;
   output out=icar.avereps n=n mean=AveRespTime;
run;

data icar.insert;
   do ID=1 to 32;
      do obs=1 to 32;
         output;
      end;
   end;
run;

data icar.avereps;
   merge icar.avereps icar.insert;
   by ID;
run;
```
data icar.final;
  merge icar.avereps(where=(obs=1) rename=(AveRespTime=ART1))
    icar.avereps(where=(obs=2) rename=(AveRespTime=ART2))
    icar.avereps(where=(obs=3) rename=(AveRespTime=ART3))
    icar.avereps(where=(obs=4) rename=(AveRespTime=ART4))
    icar.avereps(where=(obs=5) rename=(AveRespTime=ART5))
    icar.avereps(where=(obs=6) rename=(AveRespTime=ART6))
    icar.avereps(where=(obs=7) rename=(AveRespTime=ART7))
    icar.avereps(where=(obs=8) rename=(AveRespTime=ART8))
    icar.avereps(where=(obs=9) rename=(AveRespTime=ART9))
    icar.avereps(where=(obs=10) rename=(AveRespTime=ART10))
    icar.avereps(where=(obs=11) rename=(AveRespTime=ART11))
    icar.avereps(where=(obs=12) rename=(AveRespTime=ART12))
    icar.avereps(where=(obs=13) rename=(AveRespTime=ART13))
    icar.avereps(where=(obs=14) rename=(AveRespTime=ART14))
    icar.avereps(where=(obs=15) rename=(AveRespTime=ART15))
    icar.avereps(where=(obs=16) rename=(AveRespTime=ART16))
    icar.avereps(where=(obs=17) rename=(AveRespTime=ART17))
    icar.avereps(where=(obs=18) rename=(AveRespTime=ART18))
    icar.avereps(where=(obs=19) rename=(AveRespTime=ART19))
    icar.avereps(where=(obs=20) rename=(AveRespTime=ART20))
    icar.avereps(where=(obs=21) rename=(AveRespTime=ART21))
    icar.avereps(where=(obs=22) rename=(AveRespTime=ART22))
    icar.avereps(where=(obs=23) rename=(AveRespTime=ART23))
    icar.avereps(where=(obs=24) rename=(AveRespTime=ART24))
    icar.avereps(where=(obs=25) rename=(AveRespTime=ART25))
    icar.avereps(where=(obs=26) rename=(AveRespTime=ART26))
    icar.avereps(where=(obs=27) rename=(AveRespTime=ART27))
    icar.avereps(where=(obs=28) rename=(AveRespTime=ART28))
    icar.avereps(where=(obs=29) rename=(AveRespTime=ART29))
    icar.avereps(where=(obs=30) rename=(AveRespTime=ART30))
    icar.avereps(where=(obs=31) rename=(AveRespTime=ART31))
    icar.avereps(where=(obs=32) rename=(AveRespTime=ART32));
by ID Gender Age;
drop Location Alarm n obs;
run;

proc print data=icar.final;
run;

/*GLM Proc to Analyze Repeated Measures of Response Time. GLM Used to handle one missing
   data point */
proc glm data=icar.final;
  class Gender Age;
  model ART1 ART2 ART3 ART4 ART5 ART6 ART7 ART8 ART9 ART10 ART11 ART12 ART13 ART14 ART15
       ART16
       ART17 ART18 ART19 ART20 ART21 ART22 ART23 ART24 ART25 ART26 ART27 ART28 ART29
       ART30 ART31 ART32
    = Gender Age Gender*Age / NoUni;
  repeated Location 8, Alarm 4 /PrintE;
/*Standard Error Inspection*/
  lsmeans gender / stderr alpha = .05;
  lsmeans age / stderr alpha = .05;
  lsmeans location / stderr adjust=tukey adjust=bon alpha = .05;
  lsmeans alarm / stderr adjust=tukey adjust=bon alpha = .05;
run;
quit;
2. SAS Code Used to Conduct MC Tests For Response Time

```sas
libname ICAR 'C:\Documents and Settings\gfitch\My Documents\Data';

data icar.anova;
set icar.impdata;
RT = Reaction_Time__ms_;

*::::::::::::::::::::Response Time Analysis::::::::::::::::
This GLM PROC code is used to support the MC analysis of location and alarm mode for
Response Time;

proc GLM data=icar.anova;

class ID
   gender
   age
   location
   alarm;

model RT=
   gender
   age
   gender*age
   ID(gender age)
   location
   location*gender
   location*age
   location*gender*age
   location*ID(gender age)
   alarm
   alarm*gender
   alarm*age
   alarm*gender*age
   alarm*ID(gender age)
   location*alarm
   location*alarm*gender
   location*alarm*age
   location*alarm*gender*age
   location*alarm*ID(gender age) / ss3;

TEST H = gender
E = ID(gender age);

TEST H = age
E = ID(gender age);

TEST H = gender*age
E = ID(gender age);

TEST H = location
E = location*ID(gender age);

TEST H = location*gender
E = location*ID(gender age);

TEST H = location*age
E = location*ID(gender age);

TEST H = location*gender*age
E = location*ID(gender age);

TEST H = alarm
E = alarm*ID(gender age);
```
TEST H = alarm*gender
E = alarm*ID(gender age);

TEST H = alarm*age
E = alarm*ID(gender age);

TEST H = alarm*gender*age
E = alarm*ID(gender age);

TEST H = location*alarm
E = location*alarm*ID(gender age);

TEST H = location*alarm*gender
E = location*alarm*ID(gender age);

TEST H = location*alarm*age
E = location*alarm*ID(gender age);

TEST H = location*alarm*gender*age
E = location*alarm*ID(gender age);

title 'Response Time ANOVA';

*Tukey Multiple Comparison Test used for post hoc comparisons;
lsmeans     location /stderr pdiff adjust=tukey  e = location*ID(gender*age)  alpha = .05;
lsmeans     alarm /stderr pdiff adjust=tukey     e = alarm*ID(gender*age)  alpha = .05;

title 'Tukey MC Tests for Response Time';
Run;
3. SAS Code Used to Analyze Accuracy

```sas
libname ICAR 'C:\Documents and Settings\gfitch\My Documents\Data';

*::::::::::::::::::::Accuracy Analysis::::::::::::::::
Need to Analyze The between variables (Location and Alarm) using Cochran Q since they are
dependent
and the within Variables (Age Gender) using the Chi Square Test since they are independent
;

data icar.frequency;
set icar.impdata;

proc freq data=icar.frequency;
  tables valid;
  tables gender*valid / chisq;
  tables age*valid / chisq;
  tables location*valid / cmh2;
  tables alarm*valid / cmh2;
  title 'Chi and Cochran Q test for Accuracy';
  *print to excel;
  ODS HTML FILE='C:\Documents and Settings\gfitch\My Documents\Data
Analysis\ICAR_Accuracy_Output.xls' RS=none;
  proc print data=icar.frequency noobs;
  Run;
  ODS HTML CLOSE;
run;
```
libname ICAR 'C:\Documents and Settings\gfitch\My Documents\Data';

*:

Need to Analyze The within variables (Location and Alarm) using Cochran Q since they are related samples
and the between variables (Age Gender) using the Chi Square Test since they are independent samples;

*Code Data as a Front/Back Confusion if users select a target location opposite to the signal target location;

```sas
data icar.frontback3;
set icar.impdata;
if location = "front" then if User_Selection = "back"
then FB = "1";
else FB = "0";
if location = "front_left" then if User_Selection = "back_left"
then FB = "1";
else FB = "0";
if location = "front_right" then if User_Selection = "back_right"
then FB = "1";
else FB = "0";
if location = "back" then if User_Selection = "front"
then FB = "1";
else FB = "0";
if location = "back_left" then if User_Selection = "front_left"
then FB = "1";
else FB = "0";
if location = "back_right" then if User_Selection = "front_right"
then FB = "1";
else FB = "0";
*case for right and left just to balance data;
if location = "right" then delete;
if location = "left" then delete;
```

```sas
proc freq data=icar.frontback3;
tables FB;
tables gender*FB / chisq;
tables age*FB / chisq;
tables location*FB / cmh2;
tables alarm*FB / cmh2;
run;
```
5. SAS Code Used to Analyze the Directional Information Questionnaire

```sas
libname ICAR 'C:\Documents and Settings\gfitch\My Documents\Data';

data icar.direction;
set icar.directdata;
   if question = 'FL-BL' then delete;

proc means data=icar.direction;
   CLASS alarm;
   VAR Response;

*print to excel;
ODS HTML FILE='C:\Documents and Settings\gfitch\My Documents\Data Analysis\ICAR_Directional_Alarm.xls' RS=none;
   Proc print data=icar.anova noobs;
   Run;
   ODS HTML CLOSE;
run;

proc ANOVA data=icar.direction;
   class ID
      gender
      age
      question
      alarm;

model Response=
      gender
      age
      gender*age
      ID(gender age)
      question
      question*gender
      question*age
      question*gender*age
      question*ID(gender age)
      alarm
      alarm*gender
      alarm*age
      alarm*gender*age
      alarm*ID(gender age)
      question*alarm
      question*alarm*gender
      question*alarm*age
      question*alarm*gender*age
      question*alarm*ID(gender age);

TEST H = gender
     E = ID(gender age);

TEST H = age
     E = ID(gender age);

TEST H = gender*age
     E = ID(gender age);
```
TEST H = question
E = question*ID(gender age);

TEST H = question*gender
E = question*ID(gender age);

TEST H = question*age
E = question*ID(gender age);

TEST H = question*gender*age
E = question*ID(gender age);

TEST H = alarm
E = alarm*ID(gender age);

TEST H = alarm*gender
E = alarm*ID(gender age);

TEST H = alarm*age
E = alarm*ID(gender age);

TEST H = alarm*gender*age
E = alarm*ID(gender age);

TEST H = question*alarm
E = question*alarm*ID(gender age);

TEST H = question*alarm*gender
E = question*alarm*ID(gender age);

TEST H = question*alarm*age
E = question*alarm*ID(gender age);

TEST H = question*alarm*gender*age
E = question*alarm*ID(gender age);

title 'Direction Questionnaire ANOVA';

*Tukey Multiple Comparison Test used for post hoc comparisons;
means

gender /tukey e = ID(gender*age) alpha = .05;
means

age /tukey e = ID(gender*age) alpha = .05;
means

question*gender /tukey e = question*ID(gender*age) alpha = .05;
means

question /tukey e = question*ID(gender*age) alpha = .05;
means

alarm /tukey e = alarm*ID(gender*age) alpha = .05;
means

question*age /tukey e = question*ID(gender*age) alpha = .05;
means

alarm*gender /tukey e = alarm*ID(gender*age) alpha = .05;
means

alarm*age /tukey e = alarm*ID(gender*age) alpha = .05;
means

question*alarm /tukey e = question*alarm*ID(gender*age) alpha = .05;
means

question*alarm*gender /tukey e = question*alarm*ID(gender*age) alpha = .05;
means

question*alarm*age /tukey e = question*alarm*ID(gender*age) alpha = .05;
means

question*alarm*gender*age /tukey e = question*alarm*ID(gender*age) alpha = .05;

title 'Tukey MC Tests for Direction Questionnaire';
run;
6. SAS Code Used to Conduct Friedman Analysis of Ranks on Ranking Questionnaire

```
*Friedman rank analysis for question 1;
proc freq data=viewstor.Q1;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '1. The best method for presenting crash alerts to drivers';

*rank analysis for question 2;
proc freq data=viewstor.Q2;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '2. The most noticeable method in the car';

*rank analysis for question 3;
proc freq data=viewstor.Q3;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '3. The method that is least confused with other events happening either inside or outside the car';

*rank analysis for question 4;
proc freq data=viewstor.Q4;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '4. The best method for getting my attention immediately if I was distracted and not concentrating on the driving task';

*rank analysis for question 5;
proc freq data=viewstor.Q5;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '5. The method that startles me the least, that is, cause me to blink, jump, or make a rapid reflex-like movement';

*rank analysis for question 6;
proc freq data=viewstor.Q6;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '6. The method that interferes the least with my ability to make a quick and accurate decision about the safest driving action to take (brake, steer, brake and steer, do nothing)';

*rank analysis for question 7;
proc freq data=viewstor.Q7;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '7. The method that interferes the least with my ability to perform a quick an accurate emergency driving action';

*rank analysis for question 8;
proc freq data=viewstor.Q8;
    tables ID*alarm*rank / cmh2 scores=rank noprint;
title '8. The method that least annoys me if the alert came on once a week in a situation where no driving action was required';
```

*rank analysis for question 9;
proc freq data=viewstor.Q9;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '9. The method that least annoys me if the alert came on once a day in a situation where no driving action was required';

*rank analysis for question 10;
proc freq data=viewstor.Q10;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '10. The method that least annoys my passengers if the alert came on where no driving action was required';

*rank analysis for question 11;
proc freq data=viewstor.Q11;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '11. The method that appears the least out of place in a car or truck';

*rank analysis for question 12;
proc freq data=viewstor.Q12;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '12. The best method for telling me that I am in danger and need to react immediately';

*rank analysis for question 13;
proc freq data=viewstor.Q13;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '13. The method that has the greatest potential for presenting crash alert information for preventing me from getting in an accident';

*rank analysis for question 14;
proc freq data=viewstor.Q14;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '14. The best method for presenting crash alert information that gets my attention without being overly annoying';

*rank analysis for question 15;
proc freq data=viewstor.Q15;
   tables ID*alarm*rank / cmh2 scores=rank noprint;
title '15. If your vehicle could warn you of any crash threat surrounding your vehicle, which method would you prefer to have so that you can respond quickly and appropriately to the crash threat';

/*
*print to excel;
*ODS HTML FILE='C:\Documents and Settings\gfitch\My Documents\Data Analysis\[ICAR_Rank_Freq_Means]Sheet2!.xls' RS=none;
*Proc print data=icar.rankdata noobs;
*run;
*ODS HTML CLOSE;
run:
### Appendix F: Confusion Matrices

Table 18. Confusion matrix for the auditory alarm mode.

<table>
<thead>
<tr>
<th>Target Location</th>
<th>User Selection</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Back</td>
<td>Back-Left</td>
</tr>
<tr>
<td>Back</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>39.06</td>
<td>4.69</td>
</tr>
<tr>
<td>Back-Left</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>39.06</td>
<td>15.63</td>
</tr>
<tr>
<td>Back-Right</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10.94</td>
<td>0</td>
</tr>
<tr>
<td>Front</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>17.19</td>
<td>4.69</td>
</tr>
<tr>
<td>Front-Left</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>15.63</td>
</tr>
<tr>
<td>Front-Right</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4.69</td>
<td>1.56</td>
</tr>
<tr>
<td>Left</td>
<td>27</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>42.19</td>
<td>10.94</td>
</tr>
<tr>
<td>Right</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>14.06</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>107</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>20.9</td>
<td>6.64</td>
</tr>
</tbody>
</table>
Table 19. Confusion matrix for the haptic alarm mode.

<table>
<thead>
<tr>
<th>Target Location</th>
<th>User Selection</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Back</td>
<td>64</td>
</tr>
<tr>
<td>Back</td>
<td>60</td>
<td>93.75</td>
</tr>
<tr>
<td>Back-Left</td>
<td>1</td>
<td>1.56</td>
</tr>
<tr>
<td>Back-Right</td>
<td>2</td>
<td>3.13</td>
</tr>
<tr>
<td>Front</td>
<td>1</td>
<td>1.56</td>
</tr>
<tr>
<td>Front-Left</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Front-Right</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Left</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Right</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>65</td>
<td>100</td>
</tr>
</tbody>
</table>

Confusion Matrix For Haptic Alarm Mode

<table>
<thead>
<tr>
<th>Target Location</th>
<th>User Selection</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Back</td>
<td>64</td>
</tr>
<tr>
<td>Front</td>
<td>0</td>
<td>95.31</td>
</tr>
<tr>
<td>Front-Left</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Front-Right</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Left</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Right</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>65</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 20. Confusion matrix for the auditory and haptic combination alarm mode.

<table>
<thead>
<tr>
<th>Target Location</th>
<th>User Selection</th>
<th>Back</th>
<th>Back-Left</th>
<th>Back-Right</th>
<th>Front</th>
<th>Front-Left</th>
<th>Front-Right</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back</td>
<td></td>
<td>53</td>
<td>0</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>82.81</td>
<td>0</td>
<td>12.5</td>
<td>3.13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td>100</td>
</tr>
<tr>
<td>Back-Left</td>
<td></td>
<td>12</td>
<td>49</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18.75</td>
<td>76.56</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
<td>3.13</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Back-Right</td>
<td></td>
<td>0</td>
<td>1</td>
<td>62</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>15.6</td>
<td>96.88</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td>100</td>
</tr>
<tr>
<td>Front</td>
<td></td>
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<td>0</td>
<td>0</td>
<td>54</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>84.38</td>
<td>1.56</td>
<td>9.38</td>
<td>1.56</td>
<td>3.13</td>
<td>100</td>
</tr>
<tr>
<td>Front-Left</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>58</td>
<td>0</td>
<td>6</td>
<td>64</td>
</tr>
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<td></td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>90.63</td>
<td>0</td>
<td>9.38</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Front-Right</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.13</td>
<td>84.38</td>
<td>0</td>
<td>12.5</td>
<td>100</td>
</tr>
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<td></td>
<td>4</td>
<td>9</td>
<td>0</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>39</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.25</td>
<td>14.06</td>
<td>0</td>
<td>1.56</td>
<td>15.63</td>
<td>1.56</td>
<td>1.56</td>
<td>60.94</td>
<td>0</td>
</tr>
<tr>
<td>Left</td>
<td></td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>46</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>20.31</td>
<td>0</td>
<td>0</td>
<td>7.81</td>
<td>0</td>
<td>71.88</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
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<td>59</td>
<td>84</td>
<td>57</td>
<td>71</td>
<td>66</td>
<td>48</td>
<td>58</td>
<td>512</td>
</tr>
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<td></td>
<td></td>
<td>13.48</td>
<td>11.52</td>
<td>16.41</td>
<td>11.13</td>
<td>13.87</td>
<td>12.89</td>
<td>9.38</td>
<td>11.33</td>
<td>100</td>
</tr>
</tbody>
</table>

Top Figure = Count
Bottom Figure = Percent
Table 21. Confusion matrix for the non-directional auditory and haptic combination alarm mode.

<table>
<thead>
<tr>
<th>Target Location</th>
<th>Back</th>
<th>Back-Left</th>
<th>Back-Right</th>
<th>Front</th>
<th>Front-Left</th>
<th>Front-Right</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back</td>
<td>55</td>
<td>0</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>85.94</td>
<td>0</td>
<td>9.38</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.13</td>
<td>100</td>
</tr>
<tr>
<td>Back-Left</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>87.5</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Back-Right</td>
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<td>3</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>95.31</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.69</td>
<td>100</td>
</tr>
<tr>
<td>Front</td>
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<td>0</td>
<td>0</td>
<td>57</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>1.56</td>
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Appendix G: Vitae

Greg Fitch

Education

Virginia Polytechnic Institute & State University (Blacksburg, VA)
M.S. in Industrial Engineering Human Factors Option, 2004
Thesis: Driver's Ability to Localize Auditory and Haptic Alarms in Terms of Speed and Accuracy
Advisor: Dr. Brian Kleiner

University of Toronto (Toronto, ON)
B.A.Sc. with Honour Standing in Industrial Engineering Human Factors Option, 2002
Project: Development of a Call-Management Application

Awards

Graduate Research Assistantship, 2002 - 2004
Virginia Tech Transportation Institute

Research Interests

Human Factors Engineering, Human-Computer Interface Design,
Auditory and Haptic Technologies, Crash Counter-Measure Research, Transportation Research, Computer-Supported Collaborative Work

Professional Experience

Virginia Tech Transportation Institute (Christiansburg, VA)
Graduate Research Assistant, 2002 - 2004
Supervisor: Jon Hankie, Ph.D., Advanced Systems and Crash Counter-Measure Research Center

Cognos (Ottawa, Canada)
User Interface Designer, 2000 - 2001
Supervisor: Scott McEwen, M.S., User-Interface Design Team Director

Human Factors North Consulting (Toronto, Canada)
Part Time Assistant, 1999
Supervisor: Alison Smiley, Ph.D.
Cognitive Engineering Lab, University of Toronto (Toronto, ON)
Undergraduate Student Summer Intern, 1999
Supervisor: Kim Vicente, Ph.D.

Papers

Posters

Professional Organizations
- Human Factors and Ergonomics Society (HFES)
- Acoustical Society of America (ACA)
- Canadian Society of Industrial Engineers (CSIE)

Service
- Virginia Tech Human Factors and Ergonomics Society Student Chapter President and Website Administrator, 2003 - 2004
- Big Brothers Big Sisters Volunteer, 2003 - 2004
- Industrial Engineering Club Chair and Website Administrator, 2001 - 2002
- New College Residence Council Vice President, 1999
- GrAde Expectations Math Tutor, 2000

References
- Brian Kleiner, Ph.D.
  Director, Macroergonomics and Group Decision Systems Laboratory
  Grado Department of Industrial and Systems Engineering
  Virginia Polytechnic Institute and State University
  250 Durham Hall
  519-E Whittemore Hall
  Tel: (540) 231-4926
  Fax: (540) 231-3322
Email: bkleiner@vt.edu

- Dr. Raymond J. Kiefer, Ph.D.
  Director, General Motors Structure and Safety Integration Center
  Tel: (586) 986-7032
  Email: raymond.j.kiefer@gm.com

- Dr. Jon Hankey, Ph.D.
  Director, Center for Advanced Safety Systems
  Virginia Tech Transportation Institute
  3500 Transportation Research Plaza, Blacksburg, VA 24061
  Tel: (540) 231-1500
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