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16. Abstract

This document reports work performed under contract DTNH22-91-C-07004, "In-Vehicle Crash Avoidance Warning Systems: Human Factors Considerations". The purpose of warning sounds is to alert a driver of potential roadway hazards detected by an in-vehicle crash avoidance warining device. This study investigated acoustical localization of the warning sound as a means of indicating hazard location. The research focused on several factors; speed and accuracy of responses, the effects on performauce of sound type, speaker location, and using speaker pairs to provide directional cues. The study involved subjects responding to alarms of various types and from various locations within a Ford Taurus while they performed an auxiliary task. Under the conditions of this experiment, subjects were able to localize the direction of a warning signal with reasonable speed and accuracy. This indicates that directional acoustic cues have the potential to speed driver response to hazards. However, there was meaningful variation among alternative warning sods and speaker locations. Auditory warnings should not be viewed as generally adequate for localized warnings without consideration of the signal and source. The better-performing sound/speaker combinations of this study led to broadly correct, though imprecise, orientation, with relatively few perceptual reversals. Performance appears promising, though generalizability of the implications is reserved until validation and additional vehicle types and environmental conditions can be confirmed.

7. Key Words

ITS, crash avoidance warnings, alarms, localization

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ACOUSTICAL LOCALIZATION OF IN-VEHICLE CRASH AVOIDANCE WARNINGS AS A CUE TO HAZARD DIRECTION

by
Adrian K. Tan
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ABSTRACT

An experiment was conducted to determine the effects of warning sound type, speaker location, and age on the ability to localize the direction of warning sounds in a passenger vehicle. The purpose of these warning sounds is to alert a driver of potential roadway hazards detected by an in-vehicle crash avoidance warning device. Acoustical localization of the warning sound was investigated as a means of indicating hazard locations relative to the vehicle. Four dependent variables were measured (response time, decision time, accuracy, and azimuth) to assess the speed and accuracy of localizing six different warning sounds from each of sixteen speaker locations. The six warnings were found to be appropriate for crash avoidance warning applications through a previous study. The localization task was performed in the passenger compartment of a stationary 1995 Ford Taurus sedan Subjects input their responses through a joystick The results of the study suggest that the implementation of acoustically localized crash avoidance warnings could be beneficial in the timely identification of hazard locations in the vehicle environment. Subjects were able to localize the direction of a warning signal with reasonable speed and accuracy. However, the localization effectiveness depends on the proper choice of warning sound and speaker location. Otherwise, potentially serious problems can occur if poor choices are made. Recommendations for warning sound and speaker placement were made.

ACKNOWLEDGMENTS

Dr. John Molino of Tech-U-Fit Corporation provided assistance with acoustical calibration and measurement of the experimental apparatus. His consulting services were also used in the development of the test procedure and in specification of audiometric screening criteria.

Geoffrey Steinberg of COMSIS Corporation assisted in development of the experimenter-subject protocols used throughout this study, conducted the preliminary experiments detailed in this document, and assisted throughout the study.

TABLE OF CONTENTS

1.0 INTRODUCTION

The research described in this report addresses the issue of whether the perceived location of a warning sound can be used to help drivers direct their attention in an appropriate direction for a potential hazard. A variety of vehicle-based collision avoidance systems (CAS) are emerging as part of the research and development efforts related to intelligent transportation systems (ITS). The CAS design can incorporate several devices that monitor for particular hazards, including headway distance monitors, forward obstacle detection monitors, back-up aids, blind spot monitors, and vehicle-lane position monitors, as well as devices specifically meant to observe vehicle and roadway characteristics, such as impending roll-over detectors or roadway traction monitors (Najm, 1994).

If a driver warning system is to be effective, it must quickly alert the driver to the presence and nature of a hazard. For imminent crash avoidance situations (where an immediate vehicle control response or modification of a planned response is required in order to avoid a collision), auditory warnings have generally been favored over visual displays as the primary mode for alerting the driver (although tactile displays are also receiving some consideration). Although auditory signals have a number of advantages for this situation, there are also some important limitations (Lerner, Kotwal, Lyons, and Gardner-Bonneau, 1996). There might be a variety of different CAS messages that need to be discriminated (e.g., headway warning, left blind spot, run-off-road, intersection conflict), as well as many other possible in-vehicle communications that may use an auditory cue (e.g., new information alert on a route guidance system, vehicle status warnings, cellular phone signals, driver information systems). Unfortunately, the ability of people, especially without consistent training, to learn and discriminate and rapidly respond to a range of unique auditory cues is extremely limited. Most guidance documents recommend only a few discrete signals, even with highly trained personnel such as pilots or control room operators.

Due to these requirements and concerns, it has been recommended in preliminary human factors guidelines for CAS devices (Lerner et al, 1996) that there be a single unique auditory warning that can unambiguously convey or suggest the meaning of “crash warning” whenever any CAS device is triggered. Since such a recommendation essentially eliminates the identification of the actuated device through warning sound characteristics alone, additional measures to compensate for this ambiguity must be considered so that the visual display is not relied upon for device identication; the visual modality is already heavily utilized in the driving environment.

One of the suggestions provided by Lemer et al. (1996) is to present an auditory warning in such a way that its apparent source location is consistent with the direction of the detected hazard. That is, the warning sound should appear to emanate from a position in the vehicle which is closest to the location of the hazard or crash situation which triggered the warning. For non-directional hazards, it is recommended that the warning be presented such that the driver’s attention is directed to the driver’s line of sight of the roadway ahead or toward a visual display that specifies the nature of the hazard.

Natural aural directional cueing of this type in the vehicle environment has the potential to relieve the demands placed on the visual modality required to process and extract meaning from visual formats and also to reduce display clutter (Calhoun, Janson and Valencia, 1988). The intuitive directing of the driver’s attention toward the hazard itself should also provide faster identification and response time to a hazard, given that identification of the triggered device and direction is inherently embedded within correct localization of the warning sound.

This research was an initial effort to evaluate the potential of localized auditory alarms for providing direct information to drivers about the direction of a hazard. Simulated three-dimensional auditory displays have been investigated for flight deck applications (e.g., Calhoun, Valencia, and Furness, 1987; Calhoun, Janson, and Valencia, 1988; Doll, Gerth, Engleman, and Folds, 1986), but these applications used headphones or earmuffs. This is obviously not practical in a typical vehicle. Given the complexities of an automobile interior as an acoustic field, the possible masking effects of vehicle noise, the range of hearing abilities typical of the driving public, and the range of possible auditory stimuli that might be used as warnings, it is not apparent whether drivers will be able to quickly and accurately orient to auditory alarms from various in-vehicle locations. As an initial step in addressing this issue, the present experiment presented a variety of acoustic signals, from a variety of locations, in an actual automobile environment, in the presence of realistic background noise. The abilities of listeners in the driver's seat to detect and localize the signals was measured. The research focused on providing answers to four basic questions:

- Can acoustical warnings be rapidly and accurately localized in a passenger vehicle environment?
- What type of warning sound is best for localization in the vehicle?
- Where should the speakers be located in the vehicle?
- What speaker combinations could be activated in order to localize warning signals from appropriate directions around the driver?

The scope of this study included determining how well six alternative warning signals can be localized in a vehicle environment. These six warnings were found to be potential candidates for collision avoidance warnings from a prior study (Tan and Lemer, 1995).

Speed and accuracy of localization were the primary measures of performance in this study. Specifically, the ability of each warning signal to rapidly indicate the direction of a hazard was assessed on the basis of speaker location and age using quantitative measures.

2.0 EXPERIMENT

Subjects 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 (i.e., a pair of speakers could create a virtual direction) for a total of 96 (6 x 16) different conditions.

During the experiment, one of the 96 conditions was presented and the subject's task was to determine from which direction the sound was emanating The subject input his or her response through a joystick mounted between the front seats of the vehicle just forward of the armrests. A secondary task was also presented that required the subject to watch a video tape of a vehicle driving on a highway where the camera was pointed through the front windshield of the vehicle. This task required that the subject verbally respond whenever a bridge was encountered along the video-taped route. The TV monitor for this task was mounted over the hood of the vehicle, thus requiring the subject to maintain a gaze through the front windshield. This task was included primarily to encourage the subject to maintain a relatively fixed head position during stimulus presentation and throughout the experiment. However, it also provided additional workload and prevented the subject from devoting Ml attention to the localization task A background noise recording of an interior of a vehicle while the vehicle was driving on a highway at 55 mph was continuously present. Twenty-four subjects participated in the experiment.

2.1 EXPERIMENTAL DESIGN

The experiment utilized a three-way (16 x 6 x 2) mixed factorial design. Each subject underwent 96 unique conditions. Each experimental condition was replicated 3 times for a total of 288 conditions for each subject. The factors of the experiment were Speaker activation/location (16 levels), auditory warning stimulus/Sound (6 levels), and ***Age (2*** levels).

Speaker activation and auditory warning stimulus were within-subjects variables, while age was a between-subjects variable. An equal proportion of male and female participants within each age group was achieved. Figure 2-l illustrates the experimental design Although Figure 2-l includes gender as a between-subjects variable for completeness, gender was not included as a fourth factor in the plannedanalyses (See ***Empirical Results*** section for further details).

2.1.1 Independent Variables

Speaker (16 levels). In order to test the ability to differentiate the location of sound sources within the vehicle, sixteen different speaker activation (i.e., sound source locations) levels were manipulated in the experiment. These speaker activations are listed in TABLE 2-1 below along with their respective speaker location(s) in the vehicle. The list also specifies if a single speaker or double speaker combination was used. The section entitled ***Speaker Locations*** contains additional illustrations and discussion of speaker activation levels.

Sound (6 levels). Seven different stimuli were presented during the experiment. They included 3 acoustic warnings and 3 voice warnings stimuli during data collection and one additional stimulus (acoustic warning) used during the practice session. The stimuli selected for this study were found to be likely candidates for use as auditory warnings for crash avoidance warning devices through a previous study (Tan and Lemer, 1995).

This set of six stimuli was comprised of two types of warnings-acoustical warnings and voice warnings. For the purpose of this study, acoustic warnings are defined as all auditory displays except speech displays. Speech displays or voice warnings are defined as auditory warnings which present speech in either digitized or synthesized format. Three different warnings comprised each of these warning types.

The three acoustic warnings included a low-fuel warning from an aircraft flightdeck, 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”. Both a male and female digitized voice were selected, as well as a synthesized male voice. In addition

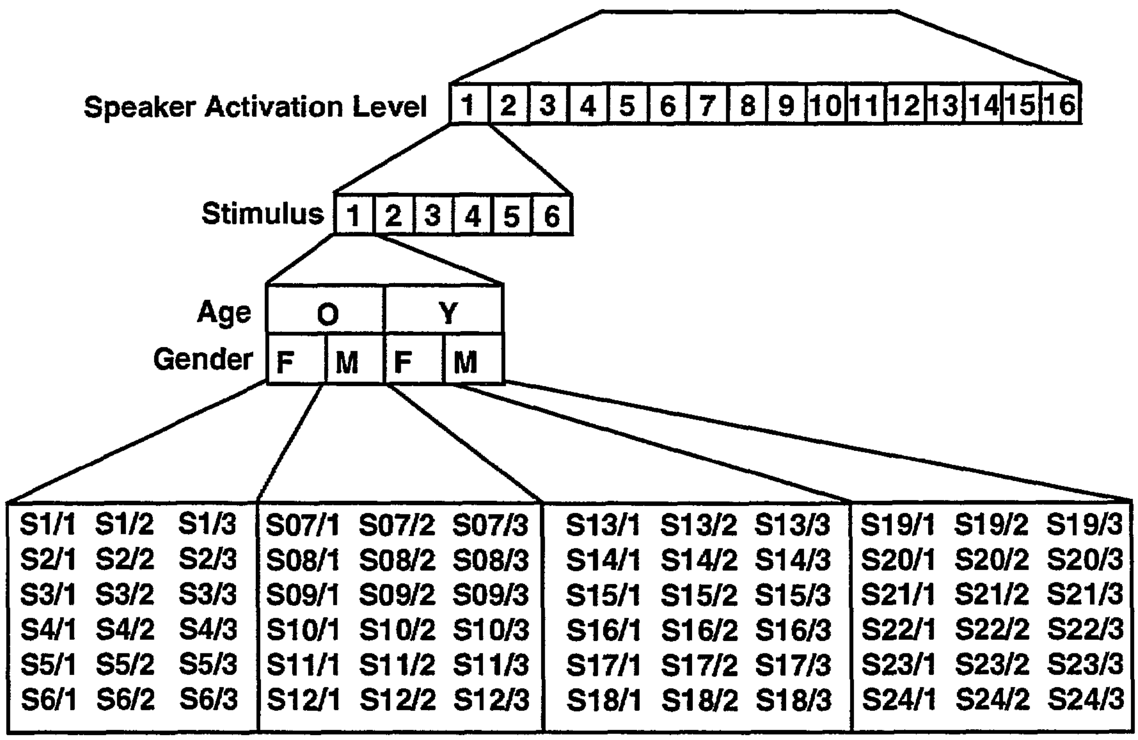


Figure 2-1. Experimental Design (See text for details of experimental conditions).

TABLE 2-l

Sixteen Speaker Activation Levels

Level	Speaker Activated	Location of Speakers in Car
1	Speaker 1 only	Left A-pillar
2	Speaker 2 only	Center of Windshield
3	Speaker 3 only	Right A-pillar
4	Speaker 4 only	Right B-pillar
5	Speaker 5 only	Right C-pillar
6	Speaker 6 only	Center of Rear Window
7	Speaker 7 only	Left c-pillar
8	Speaker 8 only	Left B-pillar
9	Speaker 9 only	Middle Right A-pillar
10	Speaker 10 only	Middle Left A-pillar
11	Speaker 11 only	Right Rear Deck
12	Speaker 12 only	Left Rear Deck
13	Speakers 1 and 3	Both A-pillars
14	Speakers 3 and 5	Right A- and C-pillars
15	Speakers 5 and 7	Both C-pillars
16	Speakers 1 and 7	Left A- and C-pillars

to these six warnings, a seventh acoustic warning was selected for use during the Practice Session (PS) for this experiment. TABLE 2-2 lists the profiles of the seven warnings.

Age (2 levels). Nested within subjects, two age groups were examined in this study. One group was comprised of younger drivers ages 20-45 (x = 25.4), while the other group was comprised of subjects 65 years of age and older (2 x 69.4). An equal number of subjects in each age group was attained.

2.1.2 Dependent Variables

Response times and perceived direction of the auditory stimulus were recorded during the experiment. Each of these measures is discussed below.

*Response times***.** Response time for localizing the sound was recorded at two points during a response, and was measured from the time the stimulus was first presented. The first measurement point occurred when the joystick *(See Apparatus* for discussion of the subject input device) was first moved away from the center position (ie., *"response time")***,** while the second measurement point occurred when the button on the top of the joystick was pressed once the joystick was positioned in the desired direction (i.e., *"decision time").* The "response time" indicates the latency for an initial detection and orienting response toward the stimulus, while the "decision tie" indicates the time required to decide on the specific direction of the perceived source and orient the joystick appropriately. For each stimulus and speaker activation level, the response time and decision time for that condition was taken as the mean of the response and decision times across the three replications.

Perceived direction of sound. The perceived direction of the sound was measured using the x- and y-coordinates input by the subject via the joystick The coordinates recorded were the values at the time the joystick button was pressed. These coordinates were then transformed into an *azimuth* heading with the center of origin concentric with the subject's head. A 0^{o} azimuth indicated that the sound was perceived to be heard as originating from directly in front of a subject. Consequently, each response made by the subject had a localized direction of between 0^{o} and 359^{o}. A fourth dependent measure inherent to the coordinate

TABLE 2-2

Descriptions of six stimulus levels and practice session stimulus.

Acoustic warnings

Level	Description	Warning Name
1	Obtrusive siren	Low-fuel aircraft warning
2	Hi-Low tone sequence	Radio Shack off-the-shelf buzzer #273-072
3	Repeating pattern	Repeating pattern

Voice warnings

Level	Description	warning
4	Male digitized voice	DANGER, DANGER, DANGER,...
5	Female digitized voice	DANGER, DANGER, DANGER,...
6	Male synthesized voice	DANGER, DANGER, DANGER,...

Practice Session warning

Level	Description	warning
PS	Repeating pattern	Repeating pattern

information was the accuracy of each response in terms of the number of degrees the response was away from a correctly localized response. For each stimulus and speaker activation level, the azimuth direction and accuracy of the response was taken as the mean of the azimuth directions and achieved response accuracies across the three replications, respectively. TABLE 2-3 summarizes the purpose of the four dependent measures and how each measure was collected.

2.1.3 Presentation Order

Experimental trials were completely randomized to minimize order effects related to treatment and practice. That is, subjects were presented with one of the six stimuli through one of the sixteen speaker activation methods at random This random assignment of trials was continued until each of the six stimuli were presented through each of the speaker activation methods ***once (6*** x 16 =96 conditions). This procedure was replicated three times yielding a total of 288 conditions.

2.1.4 Participants

Twenty-four volunteers were paid $45.00 for participation in the study. These participants were screened for age, gender, driving status, and hearing. The screening methods used are discussed in detail in the Experimental Procedures section of this document.

TABLE 2-3

Purpose and measuring method for each dependent variable.

Response Time

Dependent Variable	Purpose	Measuring Method
Response Time	Time to Initially Orient	Stimulus start to joystick movement
Decision Time	Time to Decide Direction	Stimulus start to joystick button press

Perceived Direction of Sound

Dependent Variable	Purpose	Measuring Method
Accuracy	Localization Accuracy	Degrees from correct localization
Azimuth Direction	Perceived Direction	Azimuth direction of response

2.2 *APPARATUS*

The apparatus was created around a 1995 Ford Taurus GL 4-door sedan A block diagram of the apparatus is shown in Figure 2-2. The research suite was located in a specially designed structure located in the underground parking facility of the COMSIS office site (described further below).

The stimulus presentation equipment was mounted in the passenger compartment of the vehicle and was controlled through computers and equipment placed behind and in the trunk of the vehicle (See Figure 2-3). This section discusses the apparatus components, control structure, calibration method, operating environment, and subject seating position.

2.2.1 Components

The components included twelve full-range 3.5" automotive speakers (2-way Blaupunkt RL-3524 with dome-tweeter), a Polk Monitor 6II satellite/sub-woofer system, one Infinity SM62 studio monitor speaker, two Radio Shack 3.5" automotive speakers (Model #40-1325A), a 386DW/40 IBM compatible computer controlling a second 386DX/40 IBM compatible computer (via a Vetra VIP-335 RS-232 to keyboard pipe connection) and a Keithley Metrabyte PIO-12 digital I/O board driving two Keitbley Metrabyte ERA-01 external relay boards, a Radio Shack graphic equalizer (Model #31-2025), two Kenwood stereo amplifiers (Models #KRU-5060 and #KA-791), a Radio Shack stereo mixer (Model #32-120OC), a Suncom FlightMAX analog joystick, a 20" Panasonic TV monitor, Sony VHS video cassette recorder, and a Sony digital audio tape (DAT) deck The second IBM compatible computer, controlled through the VIP-335, operated a 16-bit MediaVision Pro Audio Spectrum sound card. These components are itemized together with their functional purpose in TABLE 2-4.

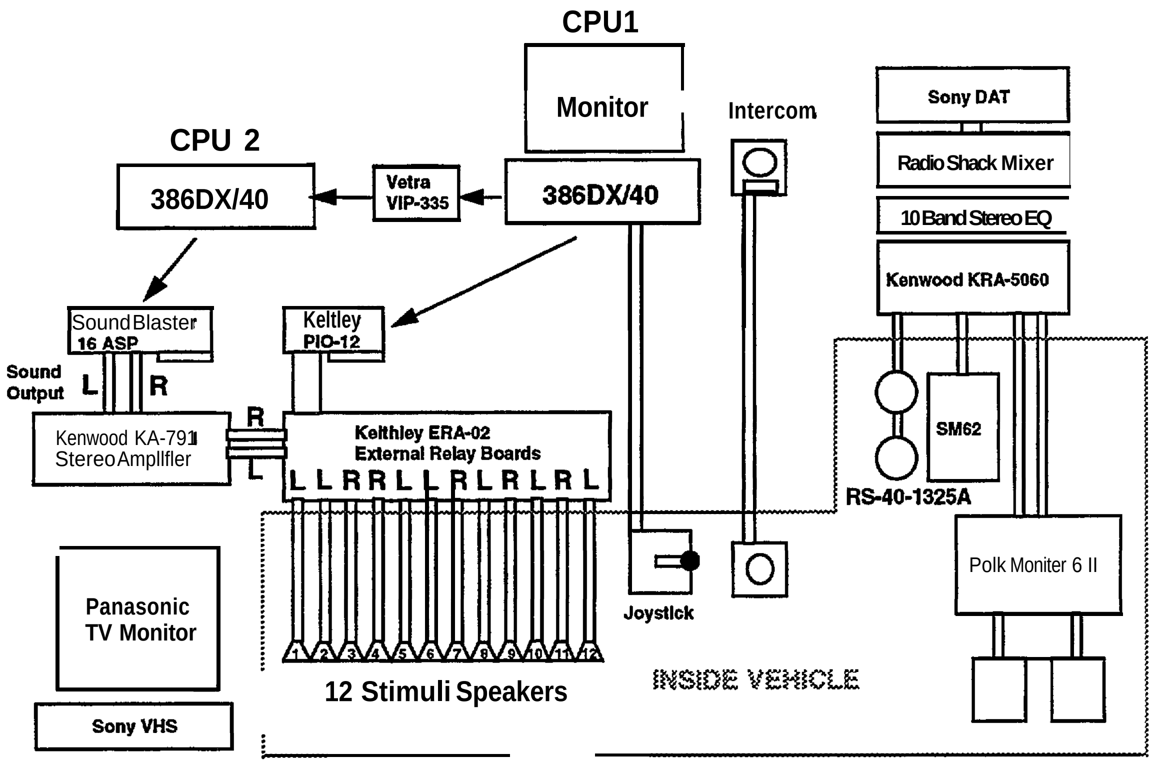


Figure 2-2. Block diagram of experiment apparatus.

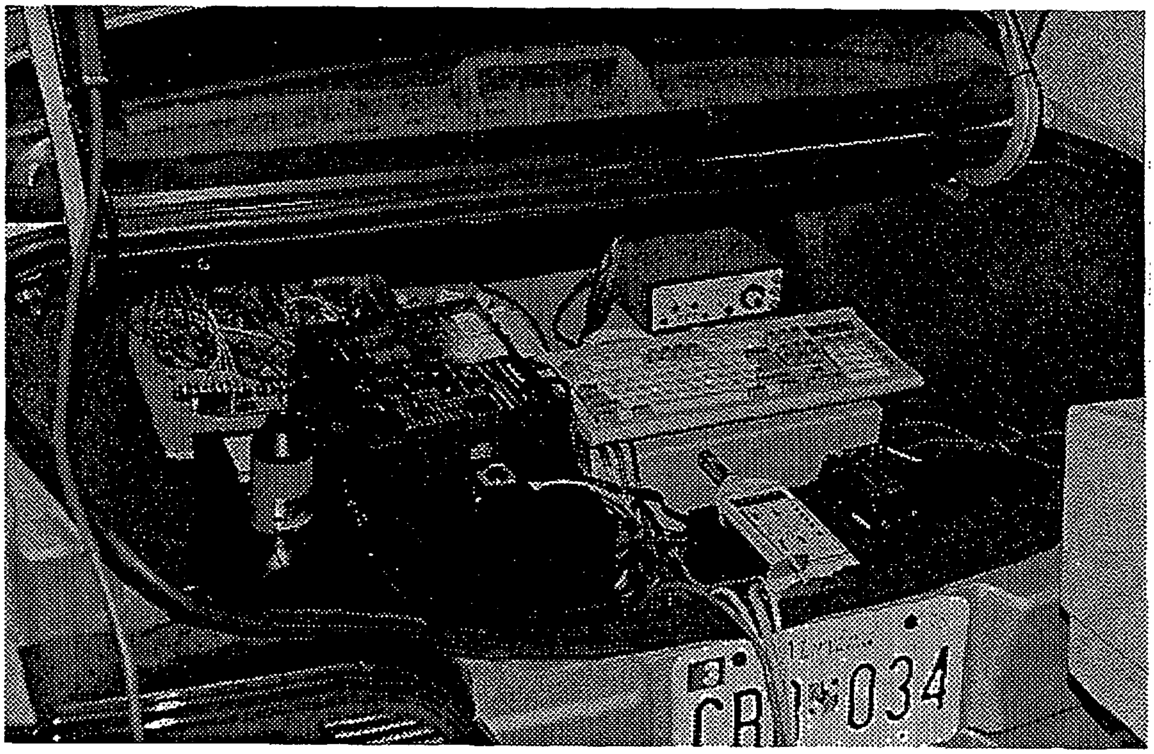


Figure 2-3. Placement of computers and equipment in trunk of vehicle.

TABLE 2-4

Listing of key apparatus components

Component(s)	Description	Purpose
CPU1	386DX/40	Experiment control
RS-232 to Keyboard Pipe	Vetra VIP-335	Controls CPU2
Digital I/O board	Keithley PIO-12	Controls ERA-01 relays
Two relay boards	Keithley ERA-01	Speaker relay circuit
Joystick	Suncom FlightMAX	Subject input device
CPU2	386DX/40	16-bit sound board control
16-bit sound board	Media Vision PAS	Stimulus signal generator
Integrated Amplifier	Kenwood KA-791	Stimulus signal amplifier
Twelve 3.5” speakers	Blaupunkt RL3524	Stimulus/speaker activation levels
DAT player	Sony DT-700	Background noise signal source
10 band equalizer	RS 31-2025	Equalize frequency response
Mixer	RS 32-1200C	Equalize background noise (P-R)
Tuner	Kenwood KRA-5060	Background noise signal amplifier
Satellite/sub-woofer system	Polk Monitor 6II	Background noise presentation
Bookshelf speaker	Infinity SM62	Background noise presentation
Two 3.5” speakers	RS 40-1325A	Background noise presentation
20” Monitor	Panasonic	Secondary task video presentation
VCR	Sony VHS	Secondary task video source

2.2.2 Control Structure

The CPU1 386DX/40 computer was programmed to control the experiment using Microsoft: QBASIC©. Stimulus presentation order, presentation times, response calibrations, and data collection were automated with the program (these are discussed in subsequent sections). The program also controlled the ERA-01 relay boards through the PIO-12 digital I/O board installed in the computer and controlled the second computer though a VIP-335 interface connected between the computers.

The twelve 3.5" speakers were driven by the Kenwood KA-791 integrated amplifier which received its input signal from the 16-bit sound board installed in CPU2. The speakers were controlled via the two ERA-01 relay boards allowing independent ON/OFF control of any combination of these speakers (each ERA-01 contained 8 mechanical relays). Loudness levels were software controlled and accomplished through independent adjustment of left and right channel output level of the sound board signals sent to the KA-791. The channel connected to each speaker was selected such that in conditions where two speakers were activated simultaneously, the left and right channel outputs each controlled one of the speakers. This method of feeding members of speaker pairs with separate channel signals allowed the loudness level of each speaker in the pair to be adjusted independently.

The DAT player provided the background noise signal via the Radio Shack mixer to the KRA-5060 amplifier driving the Monitor 6 II satellite/sub-woofer systems, SM62 speakers, and RS-30-1325 3.5" speakers. The mixer allowed adjustment of left and right input levels from the DAT to the amplifier. The Monitor 611 speakers (mounted in the rear of the car) were connected to the left channels of the Speaker A and B outputs of the KRA-5060, while the SM62 speaker and the pair of RS-30-1325 speakers (in series) were connected to the right channels of the Speaker A and B outputs (these three speakers were mounted in the front of the car). Consequently, adjustment of left and right input levels (via the mixer) allowed for sound level adjustment between the front and rear speakers. Furthermore, this arrangement allowed the L-R balance control on the amplifier to be used to turn off one set of speakers while the level on the other set was calibrated without disturbing the current settings. Subject input was recorded via a Suncom FlightMAX analog joystick connected to the CPU1 386/DX40 computer. The joystick returned x- and y-coordinates as well as button presses. The coordinate system followed by the joystick used 0,0 for the upper left most position, while maximum x- and y-values were attained at the lower right most position of the joystick

The equipment used for the secondary task included a 20” Panasonic monitor and a Sony VHS video cassette player. These were mounted on a platform that was positioned over the hood of the car in front of the windshield (See ***Environment*** section for diagram).

2.2.3 Seating/Measurement Position

Subjects were asked to seat themselves comfortably in the center of the driver’s seatpan. Each subject’s head position was adjusted so that their interaural axes were, 1) at the same height, and 2) the same distance from the top of the windshield. This was accomplished by adjustment of the 6-way power driver’s seat. A position of the inter-aural axis was selected which allowed all subjects, regardless of physical stature, to be seated comfortably. The measurement position selected was 16.5” from the top of the front windshield, 8.75” from the ceiling of the car, and centered with the steering wheel The desired head position of the seated subject was allowed to deviate ± 1” from this test position.

Although some participants would not actually sit in the testing position while driving, a single testing position was selected for this study to allow calibration to be made relative to a specific head position. Since subjects of different stature would have sat with their interaural axes at different positions once a comfortable seating position was attained, it would also have been impractical to recalibrate the aim and output Level of each speaker for each subject before experimentation. Although varying seating positions would be more realistic of the actual driving environment, maximum control of experimental variability was desired for this study to provide a foundation for future studies employing different factors, such as varying seating position.

2.2.4 Equipment Calibration

An Ivie IE-20B noise generator provided a pink noise that was used for all calibrations where frequency response equalization was required. A Quest Model 2800 sound level meter and an Ivie IE-10A sound level meter with lo-band audio spectrum analyzer were also used throughout the calibration procedures. The Ivie IE-10A was equipped with a real-time graphical display of output of the lo-band audio spectrum analyzer and accepted external inputs. This allowed the meter to be used to calibrate frequency response both electrically and through sound pressure measurement. SpectraPlus Professional v3.0, a Microsoft Windows® based spectrum analyzer, was used for all l/3 octave band frequency analyses.

The pink noise was used to calibrate the output of the sound card to ensure that frequency responses in each octave band were equalized to within ± 3 dB, with the exception of those centered below 125 Hz and above 8 KHz. This specification was selected since these bands did not comprise the predominant frequencies of the stimuli and are also difficult to achieve with the hardware. The IE-10A was connected to the line-out port of the sound card. The pink noise was recorded at 44.1 KHz sampling rate onto the computer and was then played back by the soundboard. The IE-10A was then monitored as the sound card output was calibrated. Although calibration of the soundcard was limited to treble and bass adjustment of the sound card output, the adjustments proved to be sufficient due to a flat frequency response achieved within the band of interest.

The Radio Shack equalizer was used to equalize the frequency output of the front and rear ambient noise speaker systems to within ± 3 dB across each octave band using a pink noise, with the exception of the 16 KHz octave band, at the subject's head position. Details of the acoustical calibration of the ambient noise speakers are discussed further in the ***Acoustical Calibrations*** section.

The frequency response of each of the 12 speakers were ***not*** equalized. Instead, the frequency response for each of the speakers was measured at the driver's head position and the speakers were used ***as-is (See Acoustical Calibrations*** for a detailed discussion of acoustical measurement procedures). This provided additional realism to the experiment by considering that final speaker position and type, additional passengers in the vehicle, and varying ambient noise will reduce any significant benefits of individual speaker equalization. Each of the speakers, however, was bench tested to ensure that no speaker's frequency response curve differed significantly from the group before installation (two speakers required replacement).

2.2.5 Environment

The vehicle was parked in a section of an underground parking garage where minimal noise and activity was present. A steel-framed sheetrock enclosure was then built around the vehicle and experimenter work station to provide further noise attenuation and privacy from garage patrons. Figure 2-4 illustrates the enclosure created for the vehicle and experimenter work station, as well as the general locations of the apparatus components. The experiment was conducted with the vehicle's windows closed, entertainment and climate control systems off, and the engine off. Cabin temperature did not need to be controlled due to the time of year the experiment was conducted. The vehicle was connected to an external power supply to prevent battery drainage while powering interior lighting systems and, when necessary, the climate control fan The ambient sound level within the vehicle was measured to be 49 dB(A). Subjects were seated in the driver's seat of the vehicle and received auditory stimuli, provided responses, and engaged in the secondary task from this position.

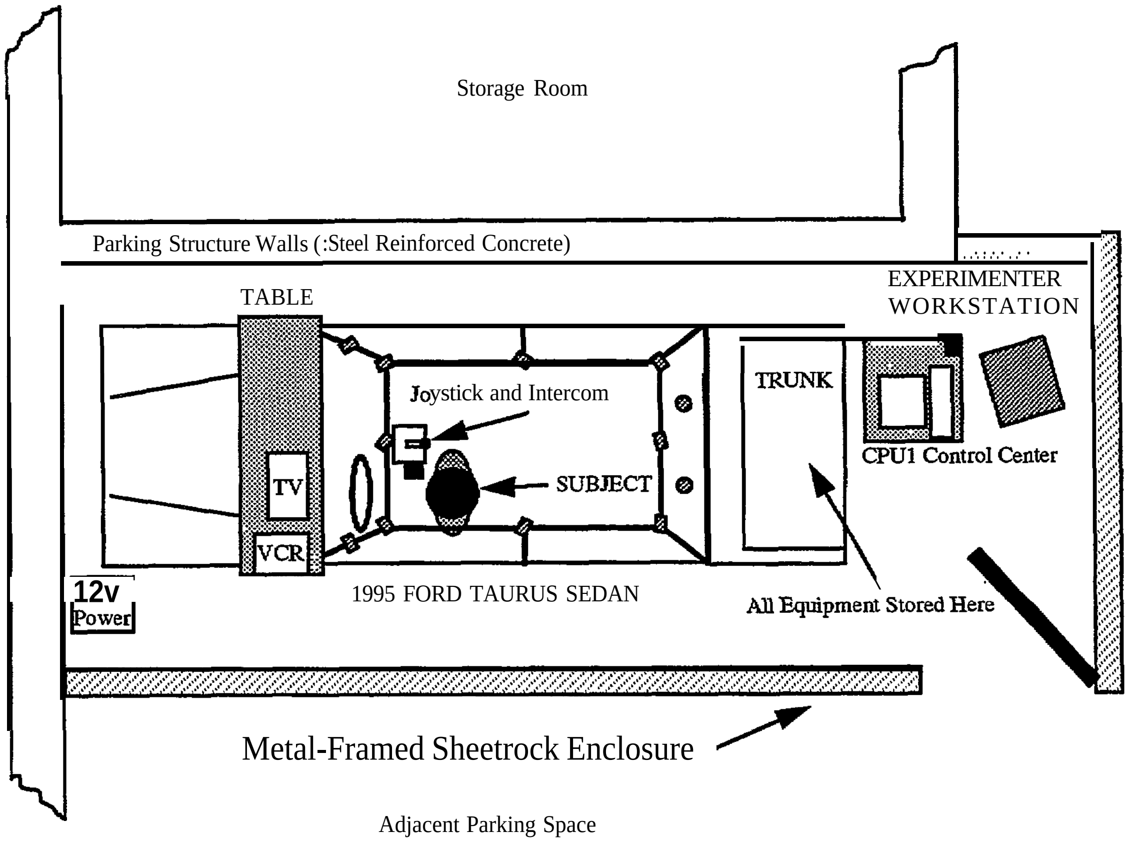


Figure 2-4. Illustration of apparatus set-up showing vehicle, expermimter's workstation, subject seating position, secondary task equipment, and stimulus speakers.

2.3 SPEAKERS

2.3.1 Stimulus Speaker Locations

Figure 2-5 provides a graphical representation of the locations of the 12 speakers within the passenger compartment of the vehicle using both a side and top view. These twelve speakers were used to present the stimuli a total of 16 different ways. The rationale for these locations was to present a sound from a direction that would correspond to typical hazard directions encountered by drivers, to utilize likely locations in the vehicle that speakers could be located, and to test the usage of existing and future stereo system speaker locations. Single speakers and pairs of speakers were activated to present a sound that appeared to emanate from various directions around the driver using the speaker locations selected.

Eight speakers were mounted along the roof-line of the vehicle-one at the top of each A-, B-, and C-pillar, one at the top center of the front windshield, and another at the top center of the rear window. Each of these speakers were aimed towards the subject's head position (i.e., measurement position), The roof-line of the vehicle was selected for these speakers to minimize the effect of obstacles, such as passengers and seating head restraints, on the warning sound, thus providing a direct sound path towards the driver's head position.

The four remaining speakers were mounted along the A-pillars and rear deck of the vehicle. Two of these speakers were mounted on the A-pillars mid-way between the top of the pillar and the top of the dashboard. Each of these speaker's axes were directed towards the center of the rear window to simulate a configuration for use by vehicle stereo systems. The two speakers on the rear deck were mounted inside the factory speaker openings and were concentric and level with the original factory speaker positions. Since these speakers were smaller than the original speakers, a baffle was fashioned around the speaker to maintain proper speaker coupling with the vehicle. In addition to the twelve speaker locations themselves, the four combinations of speakers are shown as pairs 13,14,15 and 16 in Figure 2-5. Azimuth locations of each of the 12 speakers and 4 virtual speakers relative to the subject head

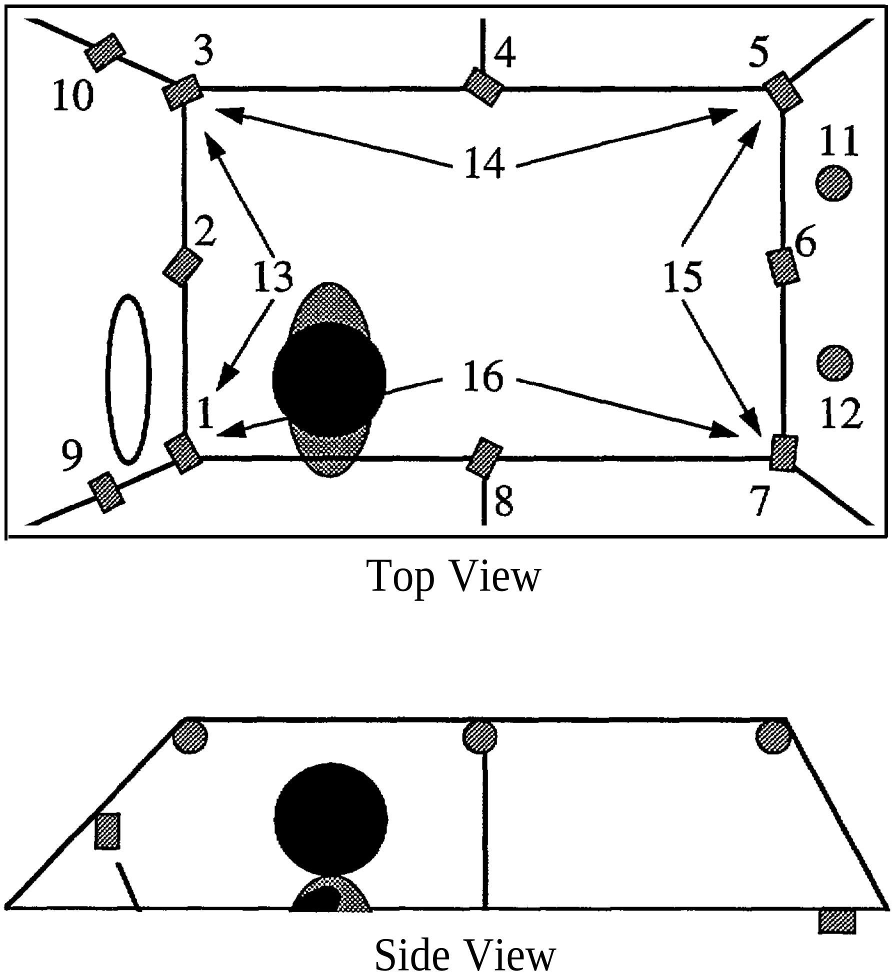


Figure 2-5. Graphical representation of 12 speaker locations within the passenger compartment using top and side views of the vehicle.

coordinate system where 0^o corresponds to directly in front of the subject's head, are provided in TABLE 2-5.

The speakers themselves were mounted within a 3" ID PVC pipe endcap (ASTM D-2729) using silicone sealant. The dimensions of this enclosure are approximately 3.5" OD, 3.25" ID and 2" in height. Each enclosure was painted flat-black and was mounted on an aluminum bracket and secured to a window using suction cups. The brackets were designed so that the speaker's axis could be aimed towards a specified point. The speakers mounted in the rear deck of the car were secured to the original speaker attachment points with rectangular PVC extensions. An acoustically transparent fabric was placed over all the speakers and along the perimeter of the roof to disguise the exact location of the speakers to reduce the tendency of subjects to visually fixate on any one speaker location, which tight influence localization responses.

Figures 2-6, 2-7, and 2-8 illustrate the 12 speaker locations as they were situated and mounted within the vehicle passenger compartment. Figure 2-9 illustrates an example of the positioning of the acoustically transparent fabric.

2.3.2 Stimulus Speaker Directionality

The directionality of the speaker used for the 12 stimulus speakers was measured to understand the frequency response of the speaker at various off-axis angles and distances from the speaker. The measurement positions were at 0^o, 5^o, 10^o, 20^o, 30^o and 45^o off-axis at one foot from the speaker. In addition, measurements at 5 feet were taken at 0^o and 45^o. A pink noise was used as the test signal The results indicated that the frequency response was similar at the two different testing distances. Figure 2-10 shows the frequency response curves for the speaker on-axis and at various off-axis angles. Higher frequencies (approximately 2,000 Hz and above) are also shown to be more directional than lower frequency sounds; however, the directionality of frequencies is evident as low as 500 Hz.

TABLE 2-5

Azimuth directions of Speaker Relative to Driver (degrees)

Speaker Locations

Level	Speaker Activated	Location of Speakers in Car	Azimuth
2	Speaker 2 only	Center of Windshield	41.1
9	Speaker 9 only	Middle Right A-pillar	57.3
3	Speaker 3 only	Right A-pillar	65.5
4	Speaker 4 only	Right B-pillar	101.1
5	Speaker 5 only	Right C-pillar	132.4
11	Speaker 11 only	Right Rear Deck	152.1
6	Speaker 6 only	Center of Rear Window	166.8
12	Speaker 12 only	Left Rear Deck	185.8
7	Speaker 7 only	Left c-pillar	203.4
8	Speaker 8 only	Left B-pillar	236.7
10	Speaker 10 only	Middle Left A-pillar .	338.5
1	Speaker 1 only	Left A-pillar	339.4

Virtual Speaker Locations

Level	Speakers Activated	Location of Speakers in Car	Azimuth
13	Speakers 1 and 3	Both A-pillars	41.1
14	Speakers 3 and 5	Right A- and C-pillars	90
15	Speakers 5 and 7	Both C-pillars	166.8
16	Speakers 1 and 7	Left A- and C-pillars	270

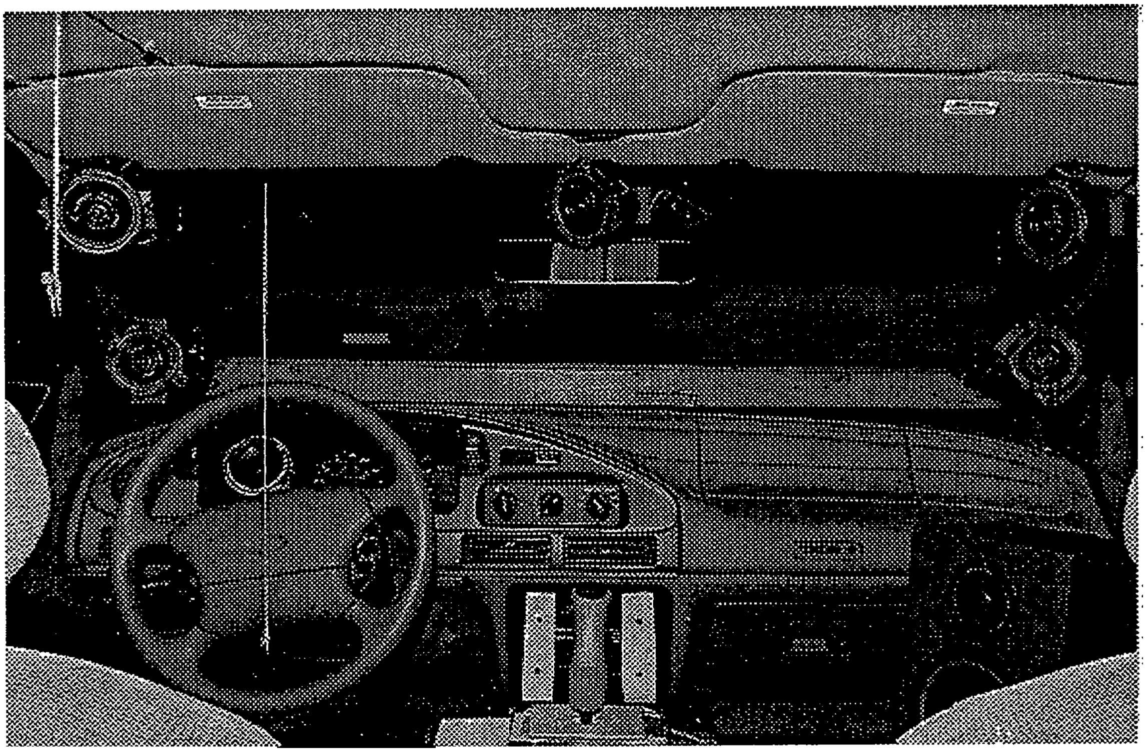


Figure 2-6. Stimulus speaker locations: Front (Note joystick and intercom at bottom center of photograph, and background noise speaker at bottom right).

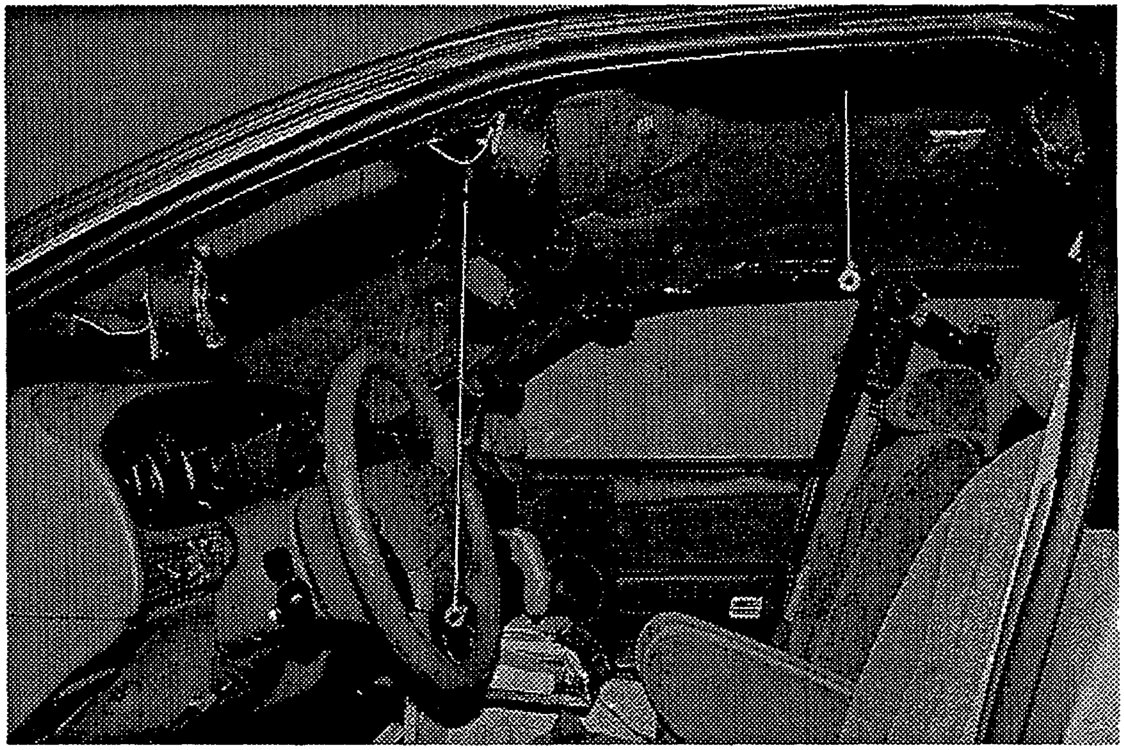


Figure 2-7. Stimulus speaker locations: Front and Side (Note measurement position (top right) marked by drop-line and center of metal washer).

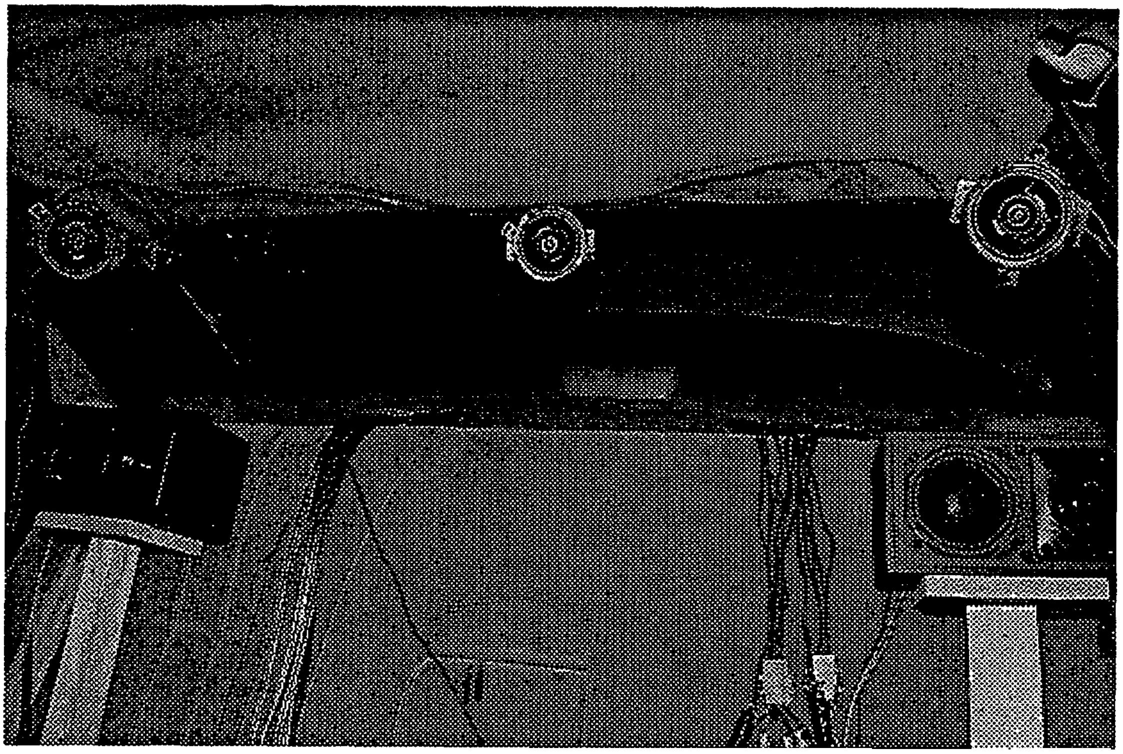


Figure 2-8. Stimulus speaker locations: Rear (Note rear background noise speakers).

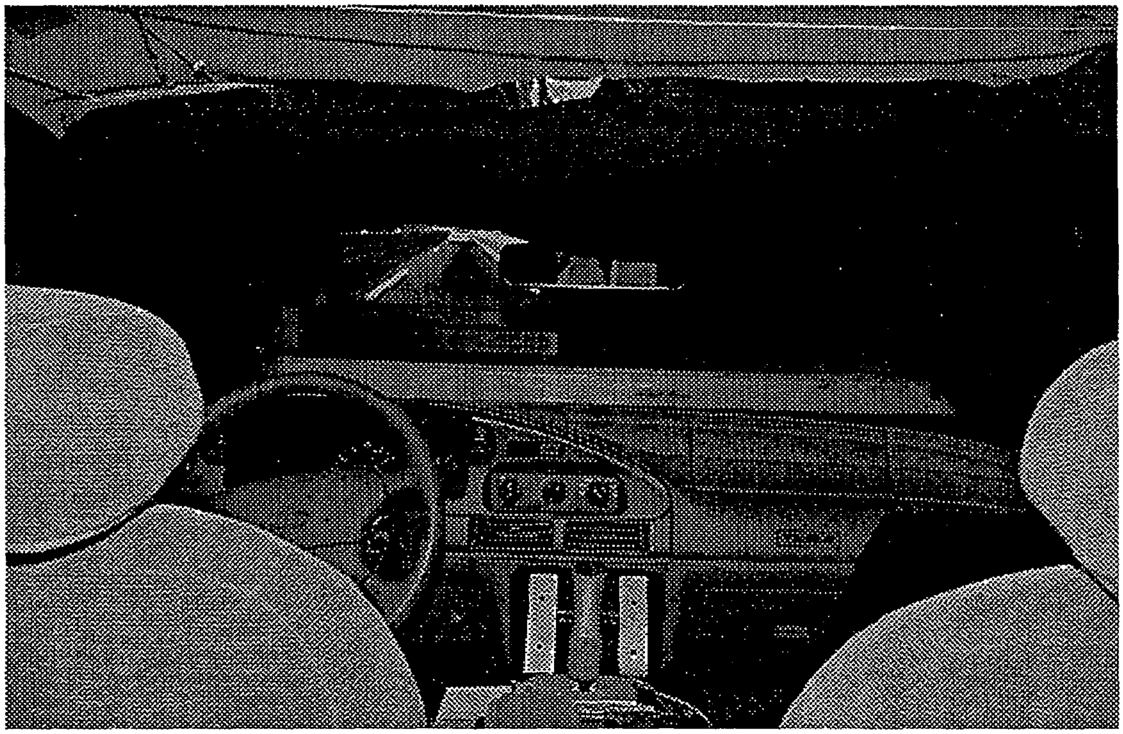


Figure 2-9. Acoustically transparent fabric positioned over front speaker (Note position of video monitor for secondary task and stored drop-line for measurement position).

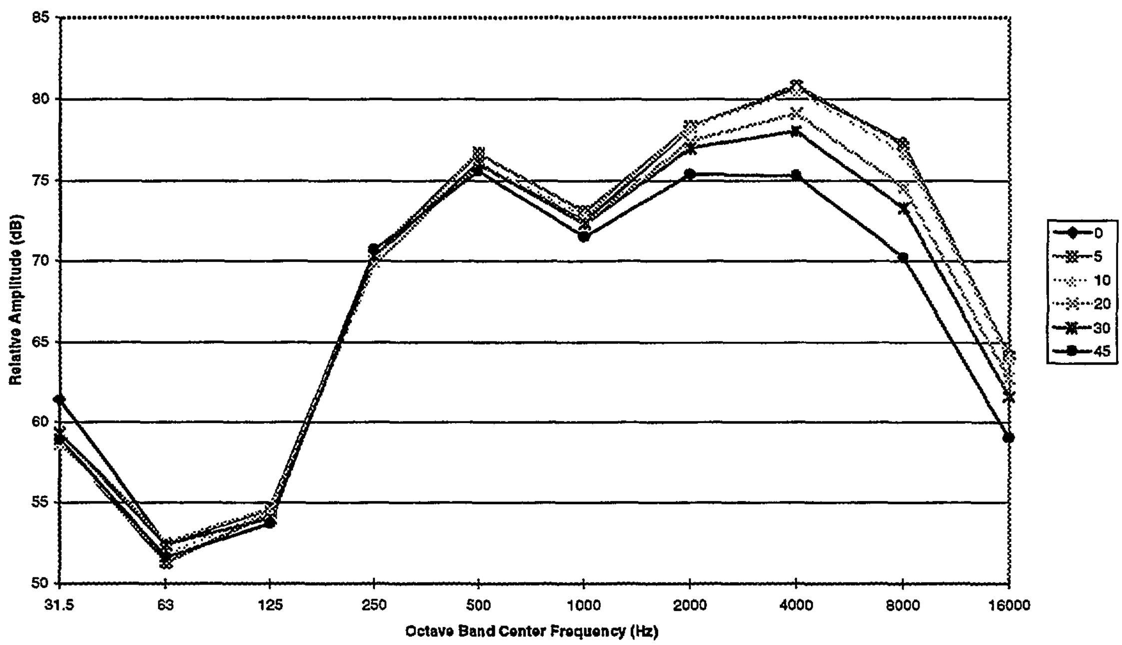


Figure 2-10. Directionality measurements of stimulus speaker frequency response.

2.3.3 Stimulus Speaker Frequency Response

The frequency response for each of the 12 speakers, as well as for the respective pairs of speakers activated simultaneously to create the 4 speaker combinations, was measured at the measurement position once the apparatus was prepared for data collection. The frequency response characteristics of the 16 measurements have been divided for illustrative purposes into Figures 2- 11, 2- 12, and 2- 13 below. These figures contain the frequency response characteristics for speakers 1 to 8,9 to 12, and 13 to 16, respectively. As the graphs illustrates, frequency response was relatively uniform across the 16 speaker activation levels. Speakers 9 and 10 and 11 and 12 performed similarly as pairs (Figure 2-12), but slightly different from the roof-line mounted group (Figure 2- 11), while speaker combinations tended to be less uniform in the lower frequencies (Figure 2-13)--a possible result of amplification and cancellation of the combined sound fronts. (Figure 2-14) contains the average performance of the 16 speakers.

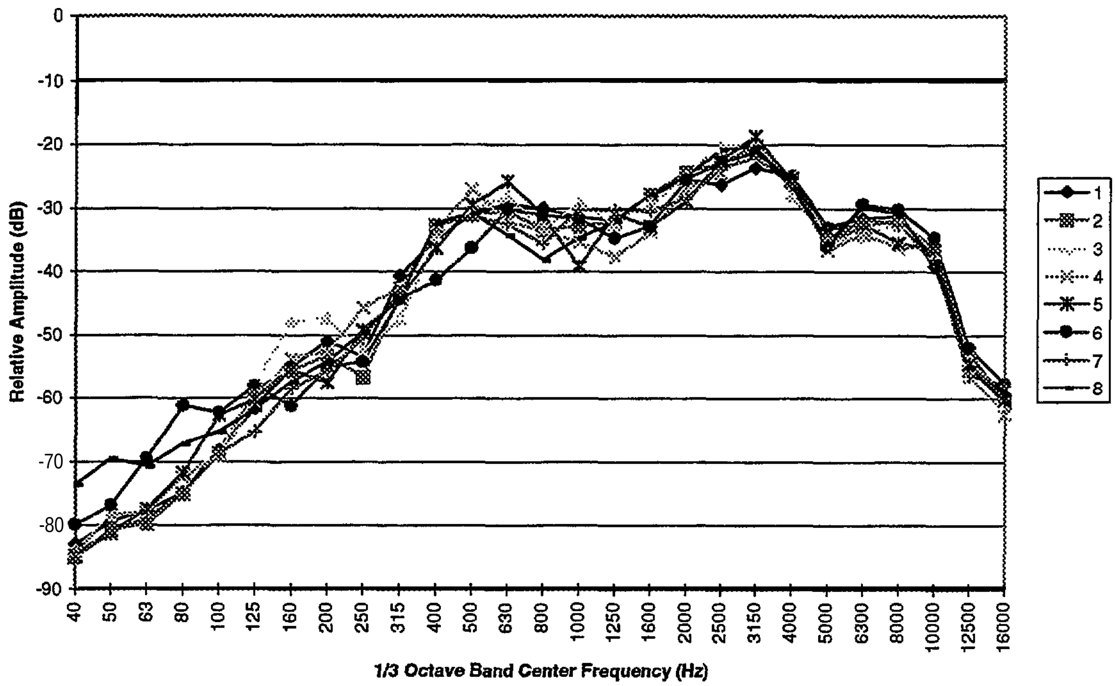


Figure 2-11. Frequency response curves at the for stimulus speakers 1 through 8 for a pink noise source (i.e., 8 roof-line mounted speakers).

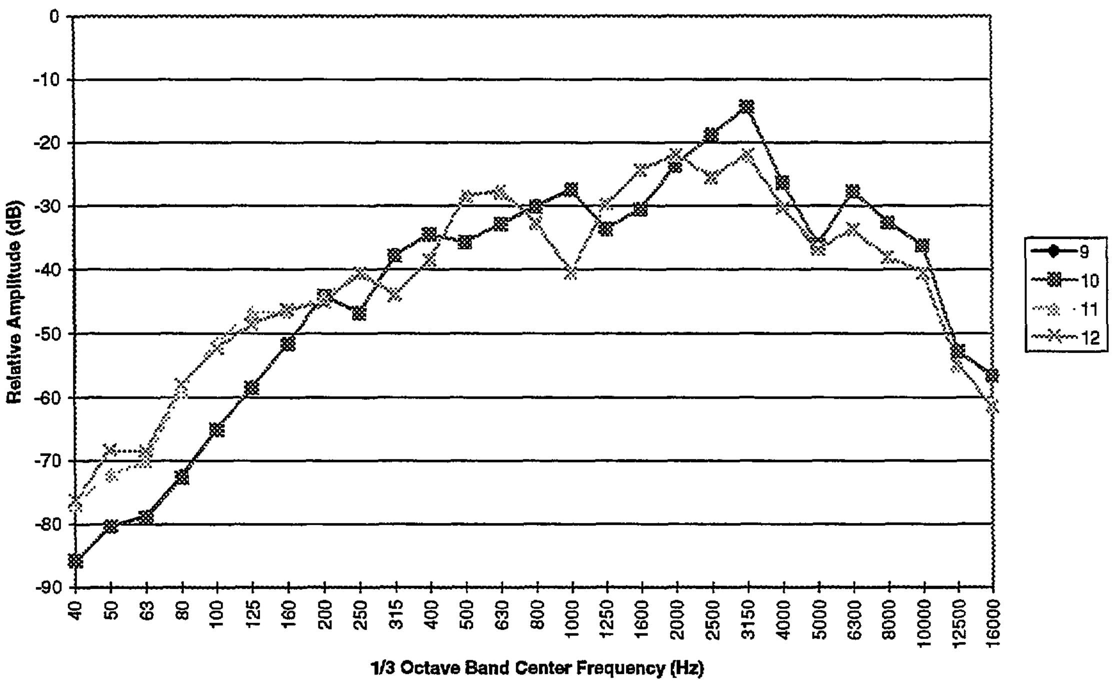


Figure 2-12. Frequency response curves for stimulus speakers 9 through 12 for a pink noise source (i.e., middle A-pillar and rear deck speakers). Notable features are a peak at 3,000 Hz for speakers 9 and 10 and valley at 1,000 Hz for speakers 11 and 12.

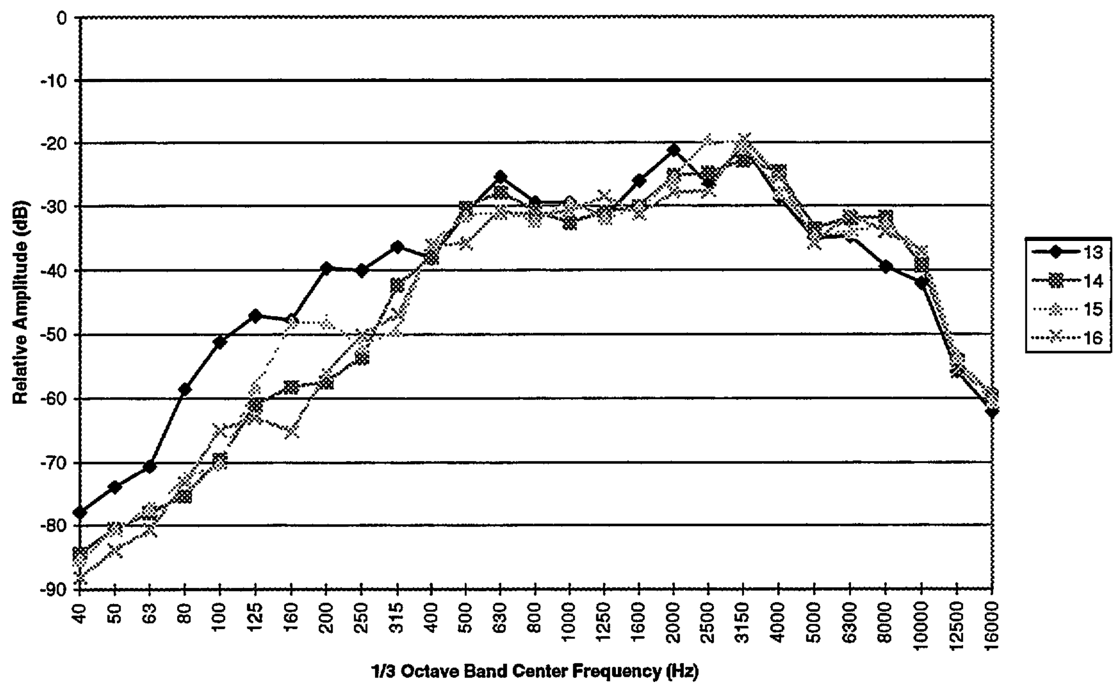


Figure 2-13. Frequency response curves for stimulus speakers 13 through 16 for a pink noise source (i.e., 4 combinations speakers; Note low frequency (< 400 Hz) interactions).

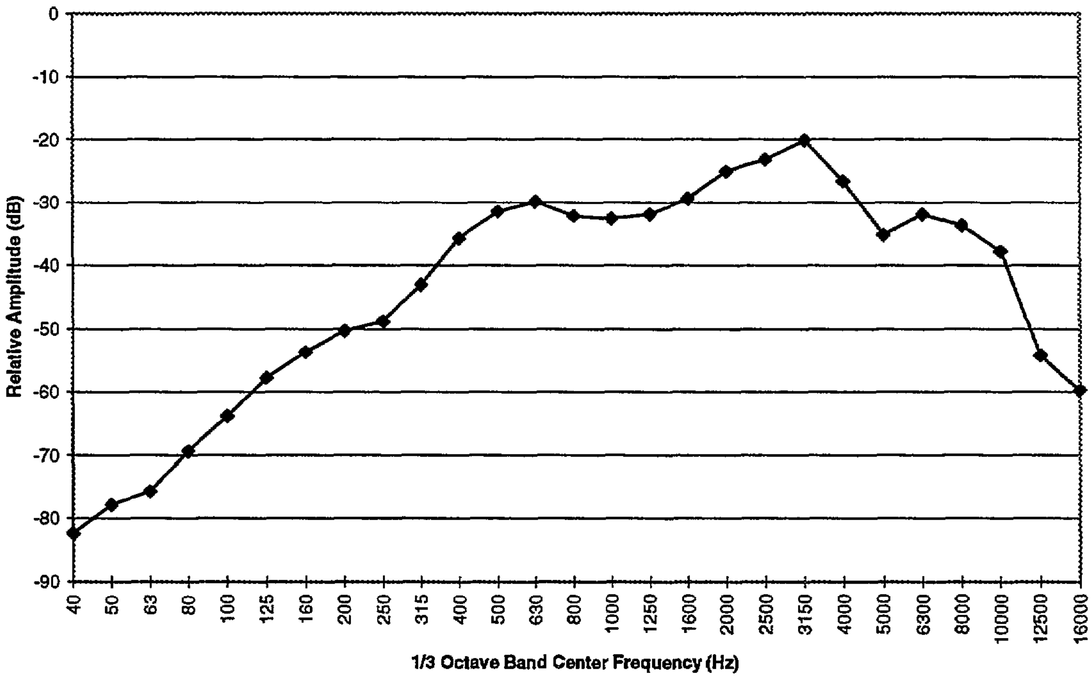
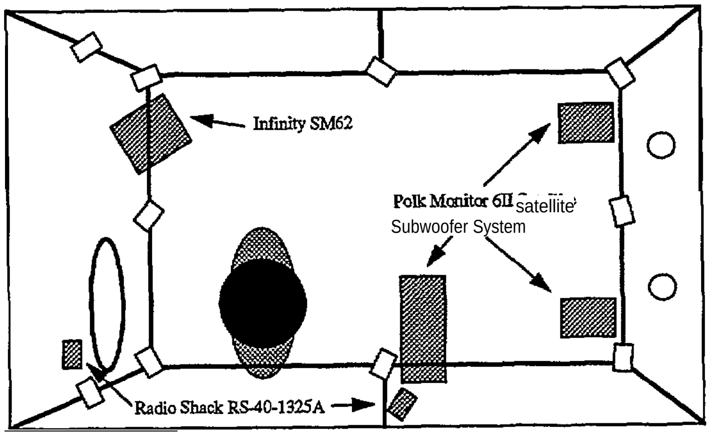


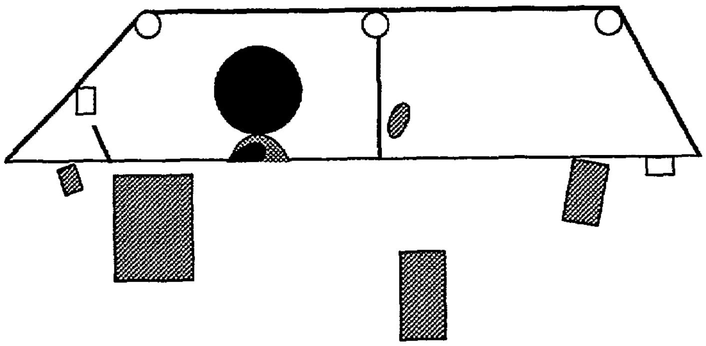
Figure 2-14. Average frequency response curves for the 16 stimulus speakers for a pink noise source.

2.3.4 Ambient Noise Speaker Locations

In addition to the twelve stimuli speakers, the sub-woofer for the Polk Monitor 6II was placed behind the driver's seat on the floor of the car. The satellites for the system were positioned on wood stands placed on the rear passenger seat. Each of these speakers were directed towards the front of the vehicle as shown previously in Figure 2-8. The speakers were positioned so that their tops were at the same height as the top of the rear seat back This positioning minimized the effect of these speakers on the sound emanating from the rear deck speakers. The Infinity SM62 speaker was placed on a wooden platform positioned at the same level but forward of the front passenger seat pan This speaker was also faced towards the driver (Refer to Figure 2-7). The two 3.5" speakers were mounted around the driver to fillout pockets where ambient noise did not appear to emanate from. One speaker was mounted directly in front of and to the left of the instrument cluster facing the driver so that it was visible through the steering wheel (Refer to Figure 2-6). The second speaker was mounted on the left side of the car slightly below and behind the driver's head and was directed towards the driver's head. This speaker was positioned using the window mounting device designed for the stimulus speakers. A graphical representation of the ambient noise speaker locations appears in Figure 2- 15. Calibration of the ambient noise speakers is discussed in the ***Acoustical Measurements and Calibration*** section.



Top View



Side View

Figure 2-15. Top and side views of ambient/background noise speaker locations.

2.4 STIMULI

The presentation format for the stimulus varied according to the warning type (voice or acoustic); however, regardless of type, each stimulus remained on or was repeated until the subject made a response. The presentation formats for the two types of warnings are discussed in the following sections.

2.4.1 Voice Warnings

The voice warning message (i.e. "DANGER") was spoken at a rate of approximately 156 words per minute (WPM) and was repeated after about 125 ms. This speech rate was recommended by Lerner et al. (1996), while the 125 ms pause between repetitions was near the minimum time required for a human speaker to clearly and accurately repeat the word for recording. Although a shorter pause between repetitions can be achieved with computer generated speech and through computer post-processing of the digitized speech, the speaker-limited pause was found to be the more natural sounding while still maintaining the desired sense of urgency.

2.4.2 Acoustic warnings

The low fuel warning and off-the-shelf buzzer warning were presented continuously until the subject made the required response. The two repeating patterns, however, were repeated at approximately 110 ms after the end of the pattern or at approximately a 75% duty cycle.

2.4.3 Stimulus Descriptions

Each of the seven stimuli are described in detail below on the basis of subjective interpretation, l/3 octave-band analyses (electrical) and time-series (i.e., time, frequency and amplitude) plots (See APPENDIX A) of samples of the stimuli waveforms. Note that for presentation purposes, the maximum dB level measured electrically with the octave-band analyses for each stimulus was adjusted to -5 dB. This was done to simplify comparison of component frequencies between the stimuli and does not imply a specific presentation method to achieve equal plot tops during the experiment. Similarly, the time-series plots in APPENDIX A have also been optimized for presentation purposes.

The actual at-ear octave band analysis of each stimulus has also been included below the electrical octave band analysis for comparison. The at-ear analysis was accomplished by recording each stimulus output from Speaker 3 (i.e., right A-pillar) onto the DAT player. These DAT recordings were then recorded to a 16-bit .WAV sound file using a sampling rate of 44.1 KHz and subsequently post-analyzed using the PC-based spectrum analyzer. Speaker 3 was selected on the basis of being forward of the pinnae of the ear and at a distance that was approximately the median distance away from the subject for the eight speakers mounted along the roof-line of the car.

It is important to note that there is a difference between the x-axis scale for the electrical and at-ear measurements for the voice warnings. This is due to the electrical measurements being made directly on the master .WAV voice recordings that were recorded using a 22 KHz sampling rate. On the other hand, the at-ear measurement recordings were sampled at 44.1 KHz, even though the master .WAV voice recordings had a maximum frequency content of approximately 11,000 Hz due to the 22 KHz original sampling rate. This frequency limitation of 11,000 Hz appeared adequate for the reproduction of the voice stimuli; however, the frequency limitation for the acoustic stimuli was 22,500 Hz.

In general, the difference between the at-ear and electrical frequency analysis is directly correlated to the frequency response of the speaker used, and the at-earfrequency response is provided merely for convenience in analysis and interpretation (See section entitled *One-Third* ***Octave Band Analysis of Stimuli at Measurement Position*** for further discussion).

Low-fuel warning. ***See*** Figure 2-16. The low-fuel warning can be described as a multiple component frequency, rapidly wailing siren that is effective in flightdeck noise. Its l/3 octave band analysis clearly shows the intent of its designer to create a warning to be heard above the flightdeck background noise. The warning ranked best at overall warning effectiveness in the Tan and Lerner (1995) study. Its time-series plot shows a continuous, full-spectrum stimulus beginning at about 800 Hz and continuing upwards.

Off-the-shelf buzzer See Figure 2- 17. The off-the-shelf buzzer purchased at Radio Shack can be described as a sequence of a high and low frequency tone, with the sequence repeated at a rate of approximately 2.25 Hz. This device was selected due to its simple warning tone sequence, compact size, and low cost.

Repeating pattern 1. See Figure 2-18. This warning stimulus was comprised of four pulses of approximately 110 ms each separated by 8 ms intervals. The four pulse pattern was repeated after 110 ms resulting in approximately an 80% duty cycle for the warning.

Repeating pattern 2 (practice session). See Figure 2-19. This warning stimulus had the same characteristics of the repeating pattern 1, but its pulses were comprised of different frequency components.

Digitized male voice. See Figure 2-20. This recorded voice was from a 32 year old male who had broadcast radio speaking experience. The phrase 'DANGER' was recorded several times using various presentation qualities. A sample recording of the phrase was made prior to the recording session and was adjusted through software to achieve the desired speech rate of 156 words per minute. This rate was then matched several times by the speaker using different voice characteristics. A mature, formal, yet not mechanical, sample of the phrase was selected.

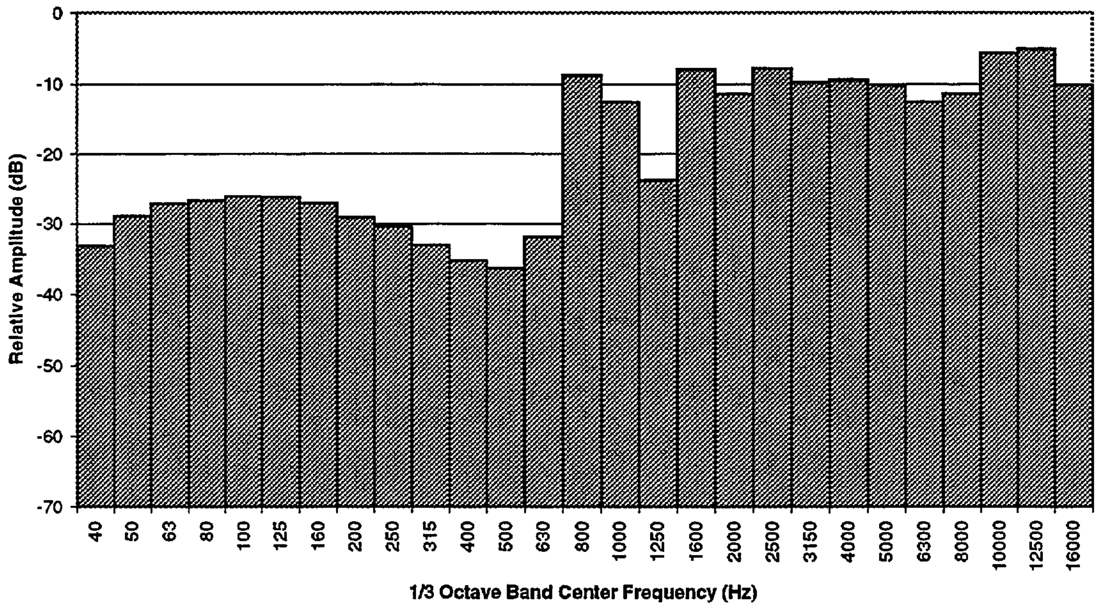
Digitized female voice See Figure 2-21. This recorded voice was from a 27 year old female with no formal broadcast speech training. The final voice sample was selected using the same methods employed for the digitized male voice sample.

Synthesized male voice. See Figure 2-22. This voice was synthesized using a Sound Blaster 16 with Advanced Signal Processing (ASP) chip. The ASP function allowed the 16-bit sound card to generate synthesized speech using the included software. The synthesized male voice characteristics were adjusted to match the desired speech rate and voice quality. It can be described as sounding computer generated, but very human like. A characteristic of the synthesized phrase was the distinctiveness in the pronunciation of the two syllables in the word

'DANGER'. Although the speech synthesis function of the soundcard performed very well, a low (but still acceptable) signal-to-noise S/N was evident with this entry-level equipment.

2.4.4 Background Noise/Description

The vehicle background noise used in the experiment was attained from a sound effects library CD that contained interior recordings of various vehicles driving under different conditions. The selected recording was that of a compact car driving at highway speeds. This vehicle size was selected as a worst-case scenario for road and vehicle noise entering the passenger compartment with the windows closed. The recording was made with the radio off and the windows closed. A l/3 octave band analysis of the background noise appears in Figure 2-23. As illustrated, the background noise contained frequencies primarily in the range of 50 Hz to 2OOO Hz.



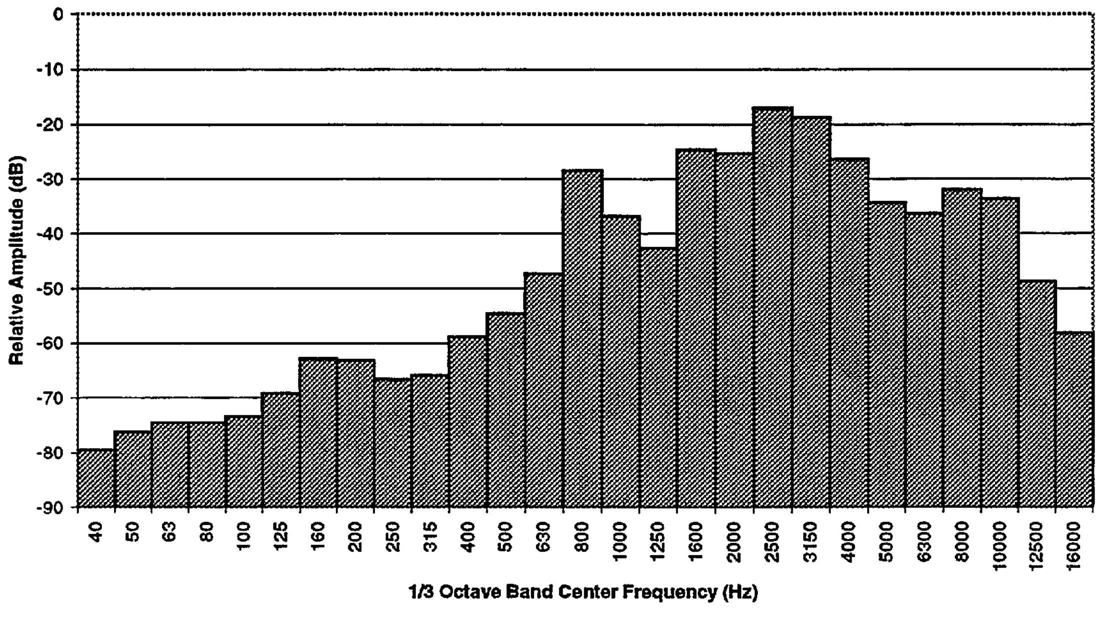
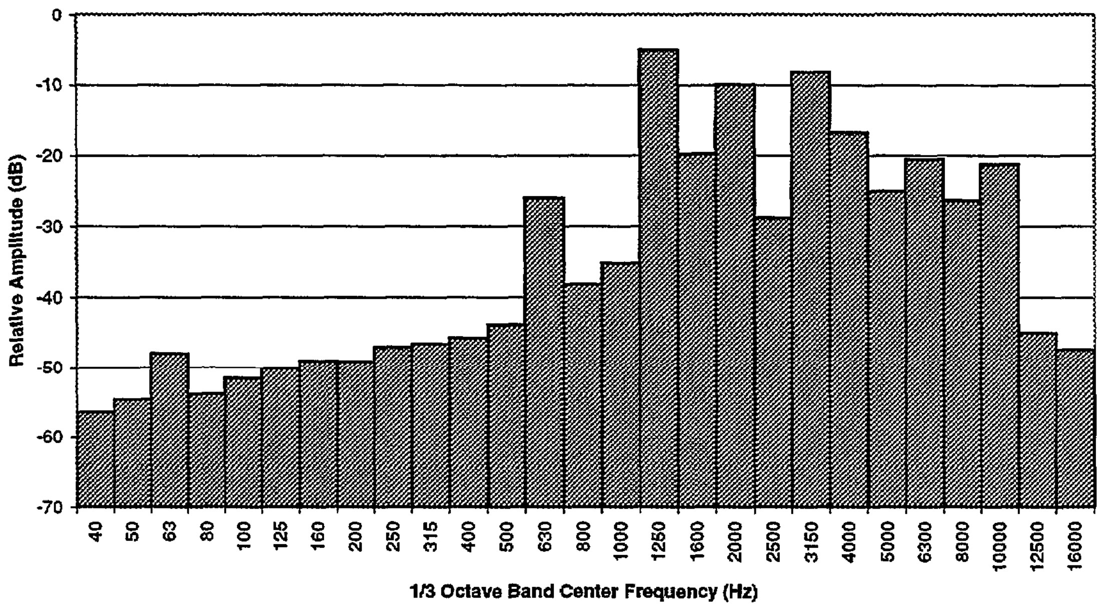


Figure 2-16. Sound/Stimulus 1: Low-fuel aircraft warning

(Top-electrical measurements, Bottom-at-ear measurements).



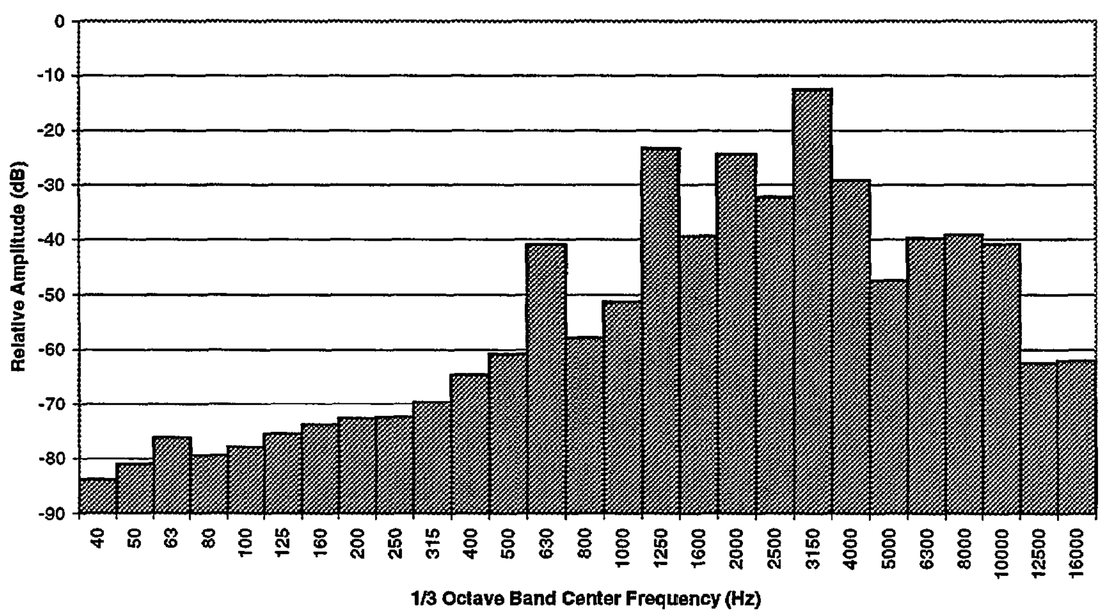
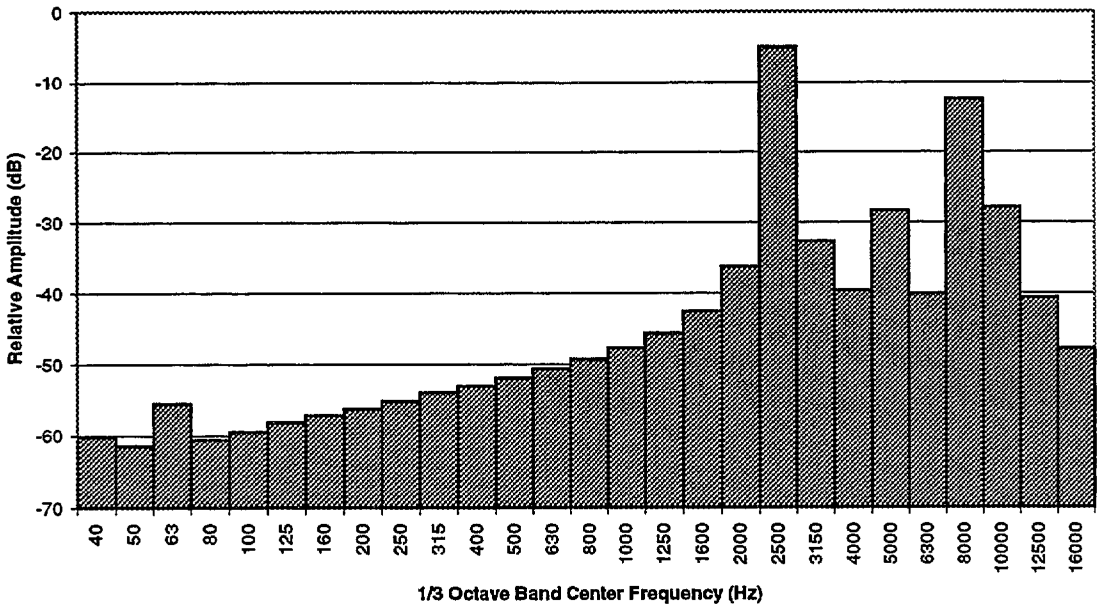


Figure 2-17. Sound/Stimulus 2: Radio Shack buzzer

(Top-electrical measurements, Bottom-at-ear measurements



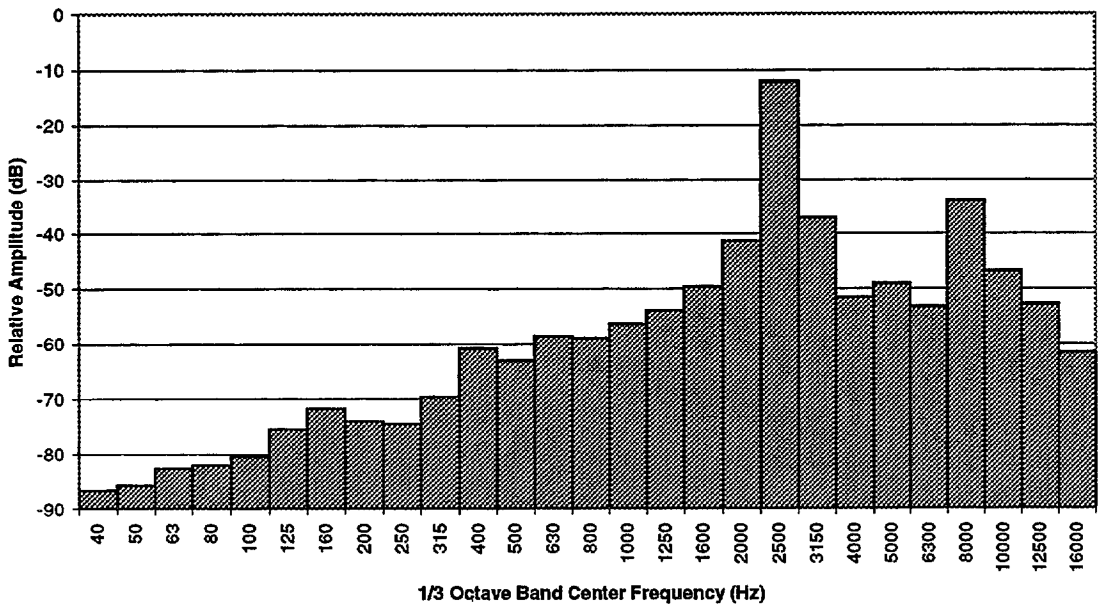
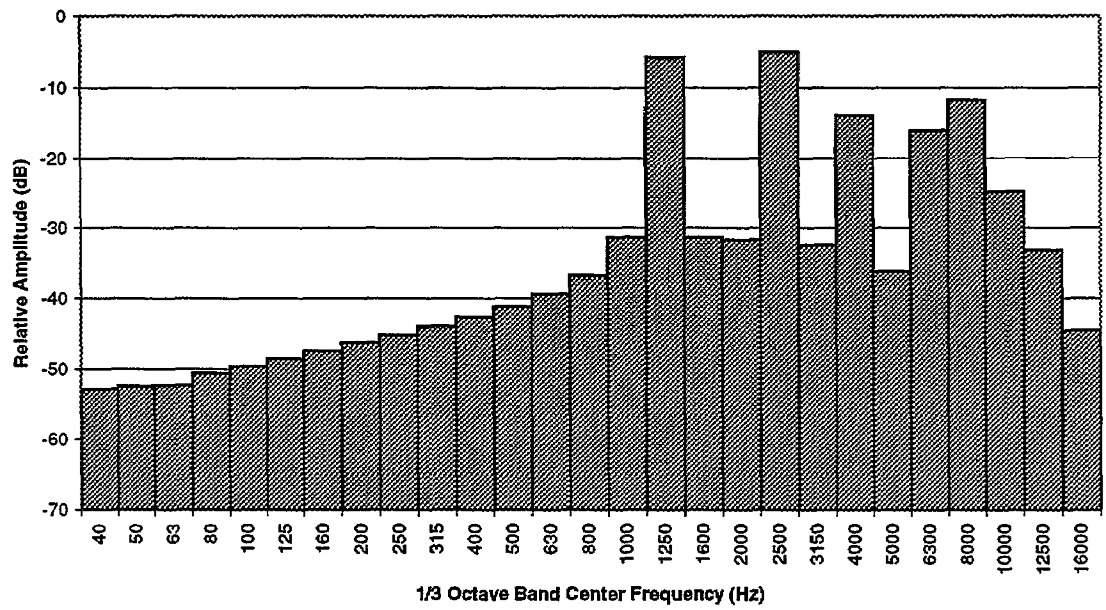


Figure 2-18. Sound/Stimulus 3: Repeating pattern

(Top-electrical measurements, Bottom-at-ear measurements).



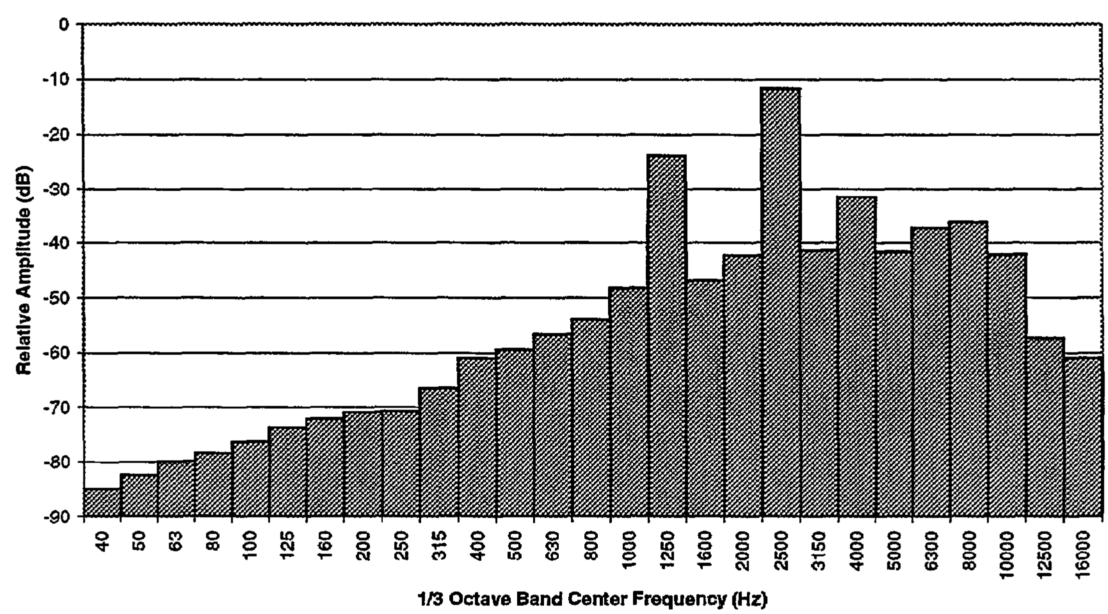


Figure 2-19. Practice Session Sound: Repeating pattern

(Top-electrical measurements, Bottom-at-ear measurements).

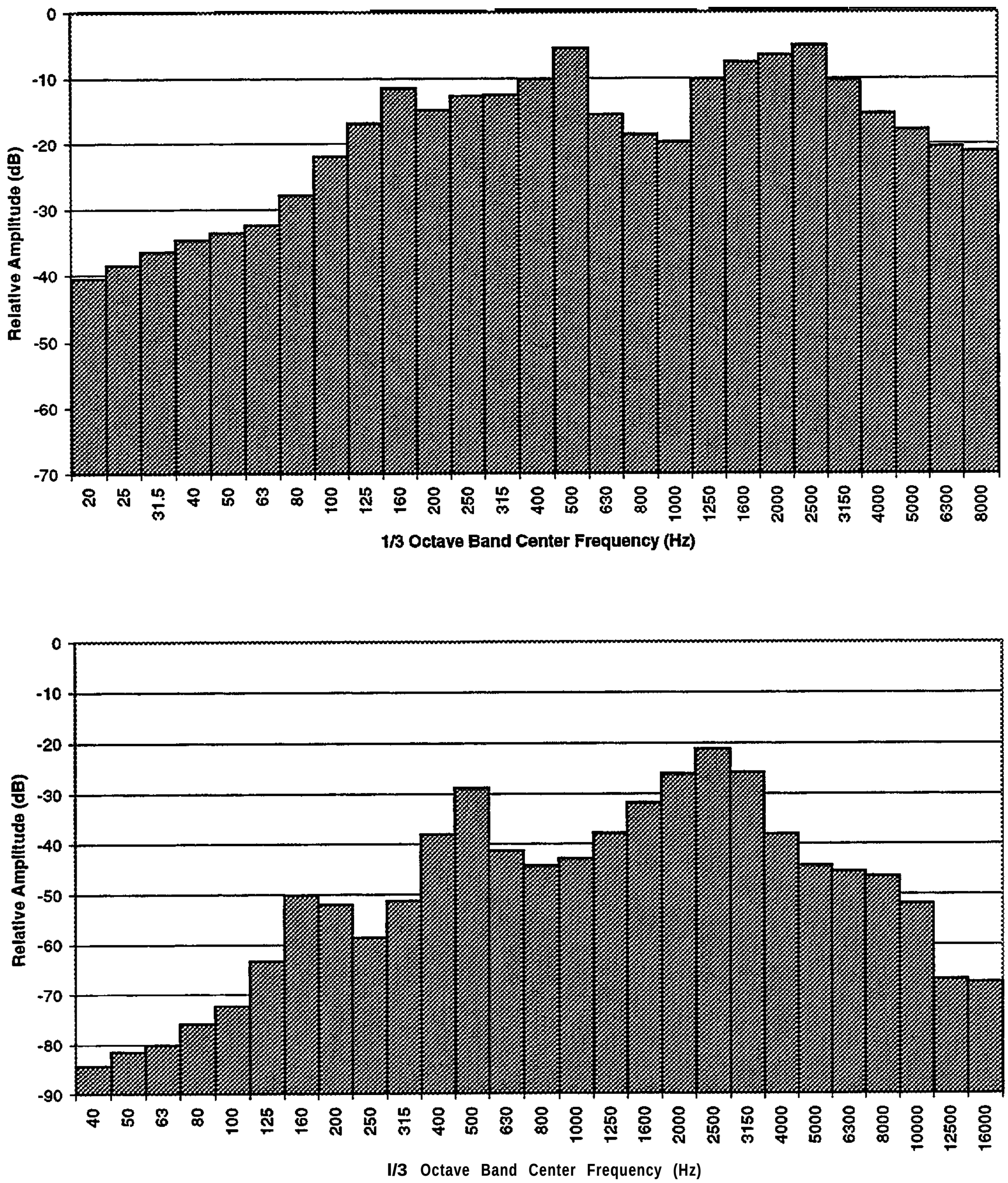
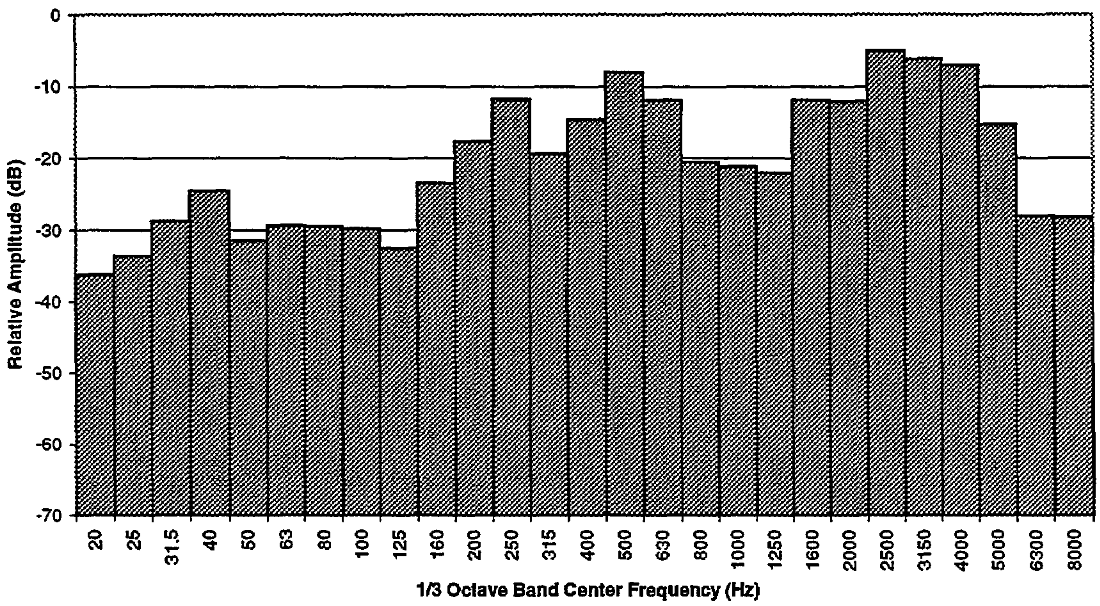


Figure 2-20. Sound/Stimulus 4: Digitized male voice (Top-electrical measurements, Bottom-at-ear measurements). Note difference in x-axis scaling (Refer to text for details).



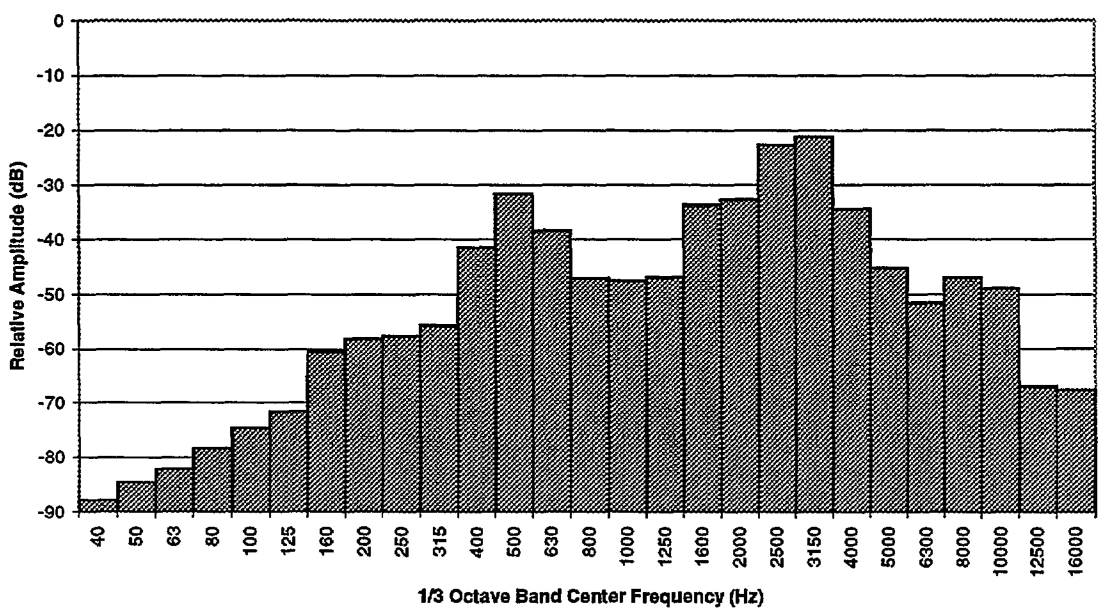
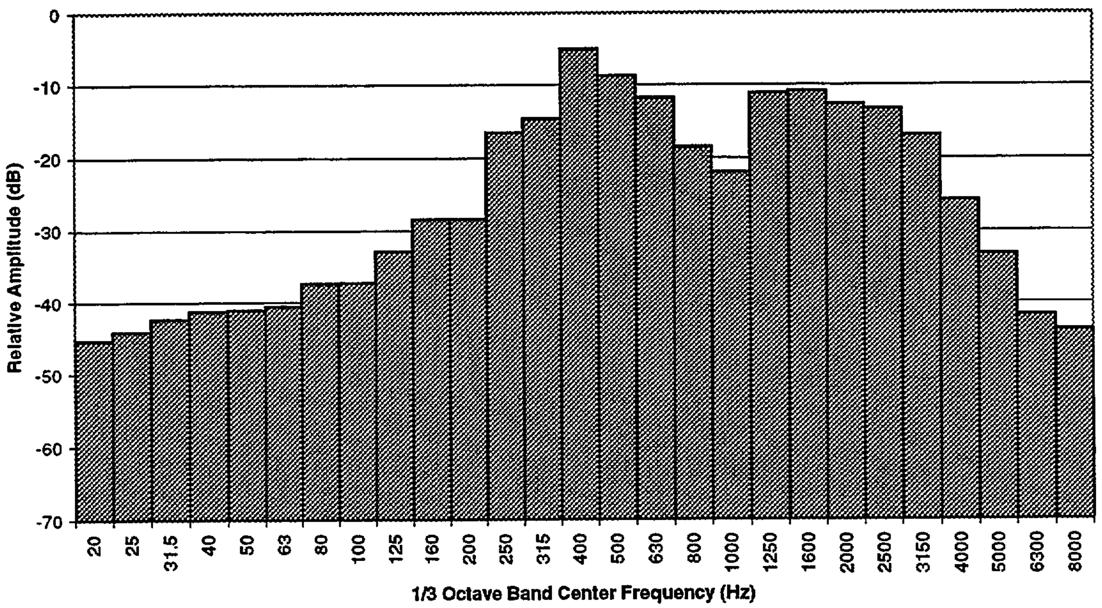


Figure 2-21. Sound/Stimulus 5: Female digitized voice (Top-electrical measurements, Bottom-at-ear measurements). Note difference in x-axis scaling (Refer to text for details).



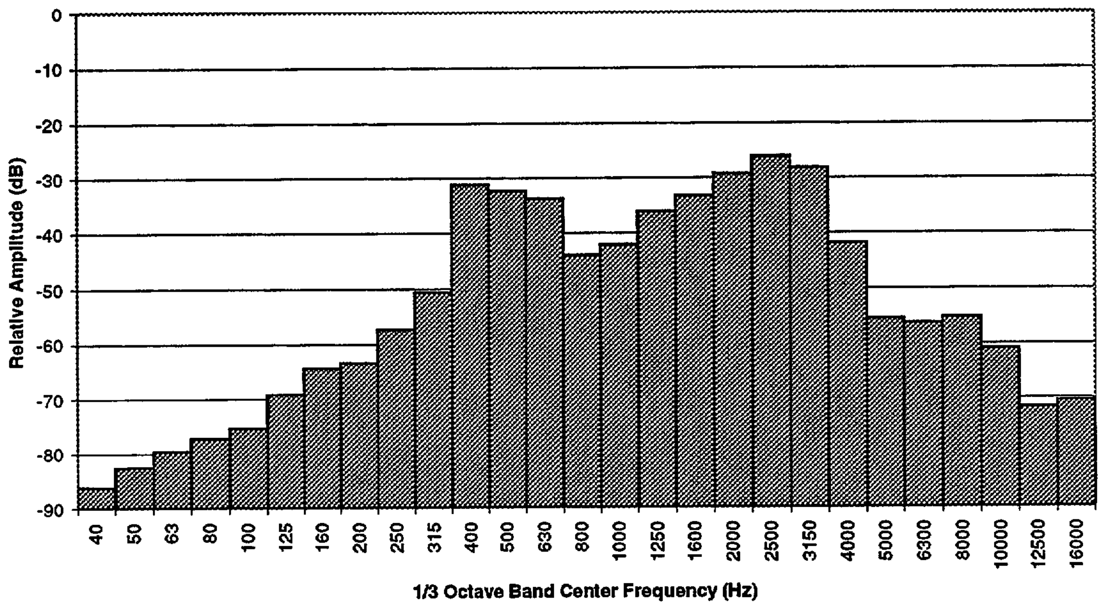


Figure 2-22. Sound/Stimulus 6: Male synthesized voice (Top-electrical measurements, Bottom-at-ear measurements) Note difference in x-axis scaling (Refer to text for details).

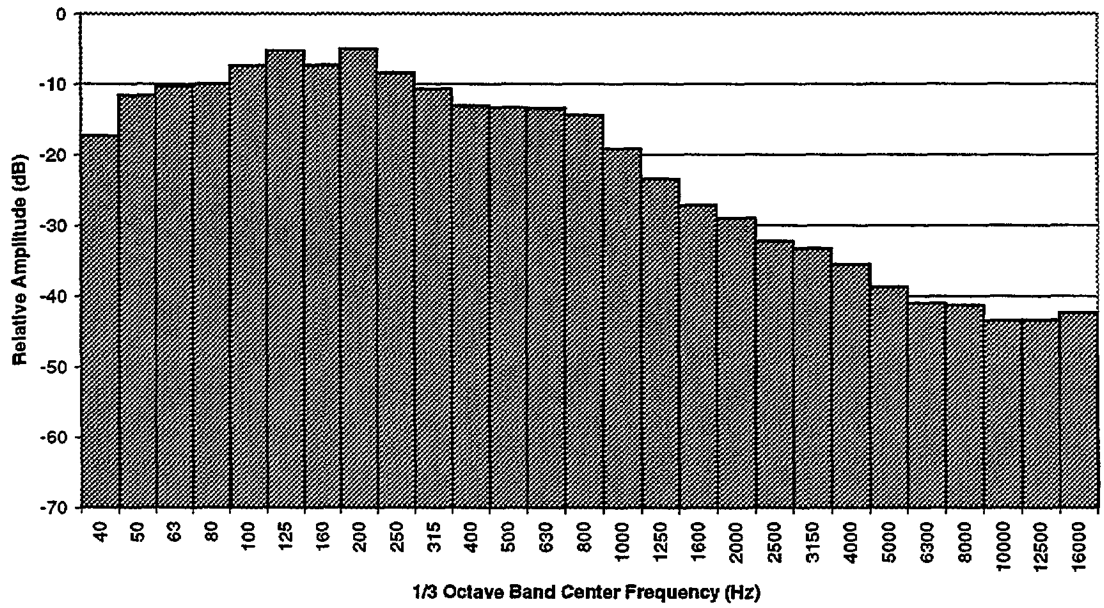


Figure 2-23. 1/3 octave band analysis of sedan background noise (electrical measurement)

2.5 ***ACOUSTICAL, MEASUREMENTS AND CALIBRATIONS***

2.5.1 Measurement Position

Depending on the measurement performed, either the Quest Model 2800 sound level meter or the Ivie IE-1OA sound level meter with lo-band audio spectrum analyzer was utilized. Each meter was mounted upright such that the microphone top was positioned at the intersection of the mid-sagittal plane and the interaural axis as discussed in the ***Seating/Measurement Position*** section. All sound measurements were made from this position except as noted.

2.5.2 Twelve Stimulus Speakers

Loudness levels from the respective speaker locations were adjusted to equal one another at the driver's head position For example, the loudness level provided by the Speaker 1 condition equaled the loudness level provided by the Speaker 1 and 3 combination Similarly, the loudness level of the Speaker 2 condition equaled the loudness level of the Speaker 8 condition. This strategy for setting loudness level was adopted to prevent stimulus loudness from being confounded within the experimental design The equal loudness between members of speaker pairs was chosen in order to introduce speaker combinations into the experiment in its simplest form--a virtual direction created exactly between the two speakers.

All stimuli loudness levels were equalized across all speaker activation conditions using the pink noise generator. A range of 2 dB(A) between the equalized levels for a single stimulus across the 16 speaker activation levels was achieved. The procedure for adjusting stimulus loudness is discussed in the following paragraphs. This range was deemed acceptable since the just-noticeable-difference (JND) for loudness is approximately ***3*** dB(A) for ***non-adjacent*** Stimuli

Each speaker's output level was adjusted using the software-controlled output level on the sound card. Since a maximum of two speakers were activated at any one time, each member of a pair of speakers was assigned either the left or the right output channel of the stereo sound card so that each could be adjusted separately (Refer to ***Apparatus: Control***

Structure section). To accomplish this calibration, a QBASICS program was written that recorded the necessary left and right channel level outputs that achieved the calibrated pink noise level measured in the pre-experiment studies ***(See Preliminary Experiments*** section) for each of the 16 speaker conditions. The measurements were made without the driver or passengers seated in the vehicle. Each of the calibrated values recorded during these procedures was then input into the QBASIC program along with their associated stimulus conditions for recall during the experiment.

2.5.3 One-Third Octave Band Analysis of Stimuli at Measurement Position

Each of the seven stimuli used in this experiment was measured both electrically and acoustically. Discussions of the electrical l/3 octave band analyses provided a description of the frequency components of each stimulus (Refer to Stimuli section). In addition to these measurements, the actual sound at the measurement position was analyzed to determine how the speakers reproduced the electrical signal. Refer back to Figures 2-16 to 2-22 that illustrate the actual l/3 octave band measurement for each stimulus at the measurement position. The results clearly indicate that the 3.5" speaker's frequency response played a significant role in the reproduction of the stimulus A noticeable band-pass effect of between 400 Hz and 8,000 Hz is present as a result of the speaker's design limitations, although frequency response did extend to 125 Hz and upwards to 12,000 Hz, but at 30 dB down in relative amplitude. In addition, the speaker accentuated frequencies in the 2,500 Hz to 3,150 Hz range, as is evident by a peak in frequency response in this region

Implications. Since the stimuli used in the experiment did not have a significant proportion of their frequency components outside of the speaker's frequency response range, the band-pass effect did not appreciably affect the characteristics of the stimulus. However, the frequency response range that was reproduced by the speakers was directly correlated with the at-ear frequency spectrum of the stimuli

All of the voice warnings contained a high proportion of the speech signal within the 2,500 Hz to 3,150 Hz range that was affected by the peak in frequency response of the speaker in this range; However, the voice warnings also contained frequency components in the 125 Hz to 315 Hz range that were not reproduced as well. The repeating pattern stimulus used in the experiment also had a major frequency component in the frequency range that was amplified. The low-fuel warning and the practice session stimulus had the highest number of suppressed component frequencies above 10,000 Hz and in the 6,300-8,000 Hz range, respectively, but were not as affected in the lower frequencies.

2.5.4 Five Background Noise Speakers

Sound pressure levels from the two sets of ambient noise speakers (ie., three located in the front and two located in the rear of the passenger compartment) were equalized so that the sound level of the front and rear speakers were equal at the measurement position. A similar method of measurement to that used for the 16 stimuli speakers was used to accomplish this requirement (i.e., meter placement, pink noise, etc.). The initial positions for the ambient noise speakers were selected on the basis of providing a relatively uniform ambient noise presentation. This was accomplished through trial and error by the experimenter first placing the five speakers throughout the vehicle in locations that appeared best for coupling the sound sources to the vehicle and providing a uniform sound field. SPL was then equalized between the front and rear.

Frequency Response. The frequency response of the ambient noise speaker array was equalized using the Radio Shack 10-band graphic equalizer and the IE-1OA real-time spectrum analyzer mounted at the measurement position The reference signal used was a pink noise presented through the array. A+ 1.5 dB frequency response was achieved within the 63 Hz and 8,000 Hz octave bands. The results of the frequency response calibration procedure appear in TABLE 2-6. Additional measurements were made to ensure that standing waves in the vehicle near the listener's head position were minimized.

Standing Waves. Standing waves are of particular concern in environments where there are fixed sound sources (i.e. providing ambient noise from speakers instead of from dynamically changing sound sources such as engine components, exhaust systems, road surface quality, and wind noise). An attempt to measure and minimize these standing waves was included in order to minimize the effect they may have on stimulus presentation

The criteria for unacceptable standing waves was met if there existed intensity differences (notches) greater than 20 dB between adjacent test frequencies at two measurement locations around the head while a 100-3,000 Hz sine-wave sweep was presented through the ambient noise speaker array by a Fordham FG-202 Function Generator. The two locations were selected to be four inches to the left and four inches to the right of the measuring point, or roughly near the pinnae of each ear of a seated subject. If notches were measured at these positions using the sound level meter, the ambient noise speakers were repositioned slightly and a measurement was then made again This procedure required that the frequency of the sine wave be manually increased in 10 Hz increments from 100 Hz to 500 Hz and in 100 Hz increments from 500 Hz to 3000 Hz and a SPL reading be recorded at each point. The 3000 Hz upper limit was chosen since the major components of the background noise are below this upper limit. The likelihood of standing waves occurring at frequencies above 3000 Hz is also unlikely due to the short wavelengths.

The results of the standing wave procedure were inconclusive due to the limited resolution achieved by the manual control dial on the function generator-- 10 Hz increments up to 500 Hz and 100 Hz increments from 500 Hz to 3,000 Hz. The results of the standing wave detection procedure, however, suggest that standing waves would not play a major role in the environment. Figure 2-24 illustrates the intensity levels exhibited throughout the sweep at the two measurement positions.

TABLE 2-6

Octave-Band Frequency Response of Ambient Noise Speaker Array

	Speakers		
Freq. (Hz)	Front (dB)	Rear (dB)	Both (dB)
32	0	0	-3
63	-3	-3	-6
125	0	-3	-6
250	-3	-3	-9
500	0	-3	-6
1K	0	-3	-6
2K	-3	0	-9
4K	0	0	-6
8K	-3	-3	-9
16K	-15	-21	-21

2.5.5 One-Third Octave Band Analysis of Background Noise at Measurement Position

A l/3 octave band analysis of the background noise at the measurement position was not conducted, since the frequency response of the ambient noise speakers was equalized to a known performance 1evel.

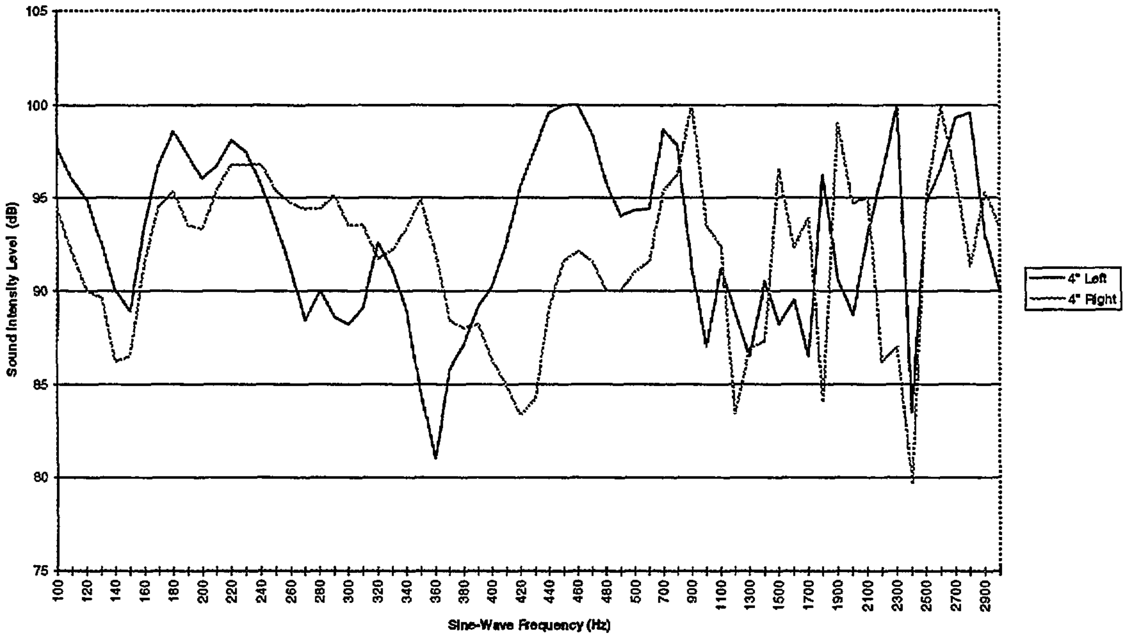


Figure 2-24. Results of standing wave analysis (Note change in x-axis scale at 500 Hz)..

2.6 PRELIMINARY EXPERIMENTS

Prior to the main experiment, two small psychoacoustical experiments were conducted to determine the appropriate stimulus presentation level and to equalize loudness across each of the seven stimuli. The presentation level and loudness levels were both determined within the vehicle background noise used in the main experiment. The background noise was presented at approximately 72 dB(A) as measured at the measurement position of the seated subject described below. Due to parallel development time of the vehicle set-up and the psychoacoustical experiments, the experiments were conducted in a laboratory environment, as opposed to the actual vehicle environment.

2.6.1 Apparatus

These experiments used a modified set-up of the main experiment apparatus. The Polk Monitor 6II satellite/subwoofer system was used to present the background noise and stimuli. The subject was seated 57" from the speaker plane. The two speakers were separated by 52", and were aimed slightly towards the subject. Acoustical measurements were made at 42.75" above the floor at the subject's seating position This measurement height was determined by first measuring the seated ear position height of the subject with the longest torso and the subject with the shortest torso and then taking the average measurement height for the test measurement position. The frequency response of the speakers was equalized at the subject's head position using the 10-band graphic equalizer. The speakers were placed against a wall of the laboratory and sound absorbing materials were positioned to minimize reverberation within the testing area and to simulate the environment of the vehicle. The materials included two 6' office partitions and a free-standing foam block approximately 6' tall. The testing area is illustrated in Figure 2-25.

2.6.2 Preliminary Experiment 1: Subjective Determination of Stimulus Loudness Level

This experiment was conducted to determine the loudness level at which to play the stimuli within the background noise. The experiment allowed 12 subjects to set the preferred

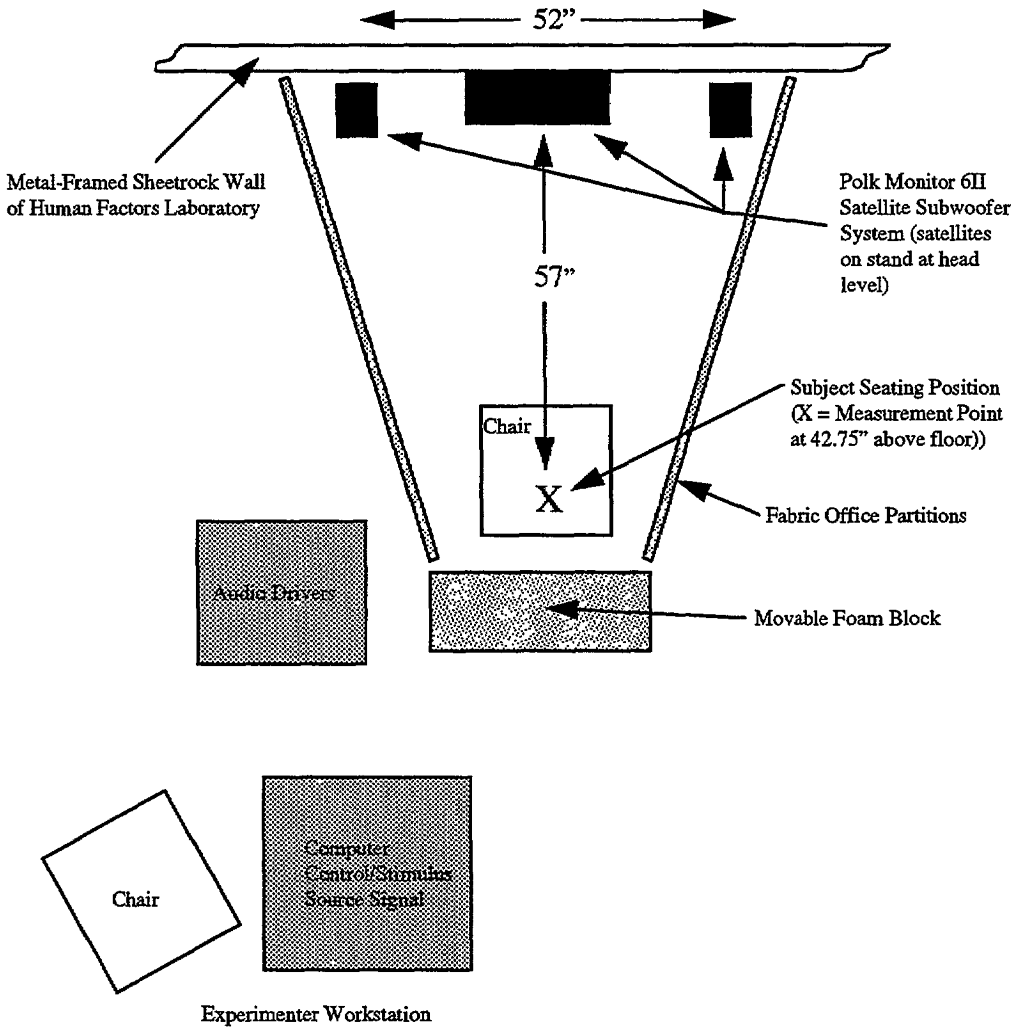


Figure 2-25. Illustration of apparatus set-up for preliminary experiments.

loudness level of one of the practice session stimuli within the background noise. Subjects (9 female, 3 male) were recruited from within the workplace and were screened only on the requirement that they have no known hearing disorders. A method of limits procedure was used where the stimulus was alternately set at either a high or low initial level. The presentation order for the high and low sequence was balanced between subjects yielding 6 subjects for each ordering.

The subject was instructed to adjust the volume of the sound until it was at the desired loudness level for an in-vehicle warning using the designated lever on the stereo mixer. A driving scenario where the warning sound might be presented was given to the subject. Each subject adjusted the sound from its initial high or initial low level to the desired setting. After each condition, the subject was asked to step out of the testing area so that the sound level meter could be positioned at the measurement position. Once the meter was positioned properly, the pink noise replaced the stimulus sound source so that a pink noise reference level could be assigned to that subject's response. The meter was then removed and the subject was reseated and given the stereo mixer. The second condition was presented after the subject indicated that he or she was ready. The pink noise measurement procedure was repeated after the second condition. This resulted in two data points for each subject.

The presentation Level determined during this experiment for the practice session stimulus was used as the reference level and stimulus for the second pre-experiment discussed below.

The results of this first experiment are shown in TABLE 2-7. The mean response for each condition was averaged across the 6 subjects participating in that condition. The mean response (pink noise reference level) across all four conditions was 74.8 dB or roughly 76 dB(A) for the test stimulus wthin the 72 dB(A) background noise.

This sound level was taken to be a reasonable estimate of a realistically acceptable warning sound level for the simulated listening conditions.

TABLE 2-7

Mean Sound Levels (dB) for Pre-Experiment One (n=6)

Order 1 (Low then High)

LOW	High	Mean
72.9	74.1	73.5

Order 2 (High then Low)

High	LOW	Mean	*Mean (all conditions)*
77.8	74.4	76.1	74.8

2.64 Preliminary Experiment 2: Subjective Equalization of Stimuli Loudness Levels

Although two complex sounds may yield similar readings on a sound level meter, the sounds may not sound equally loud to a listener. This may be due to complex transient components within the sounds which are difficult to measure with a meter, or by characteristics such as onset which might make a sound appear louder due to instigation of a startle response. For example, the existence of noise spikes (e.g. clicks), that are imperceptible to the human ear, may be picked up by a sound level meter sampling at a higher rate than the human ear causing an inflated loudness reading. In addition, complex sounds of equal sound pressure level to less complex sounds are perceived to sound louder. Consequently, adjusting each stimulus to achieve the same A-weighted sound measurement (dB(A)) at the measurement position may result in sounds which still do not sound equally loud to the subject. To account for this potential problem, a second pre-experiment study was conducted to equate loudness across the stimuli using a subjective method-of-adjustment procedure.

Twelve subjects with no history of hearing problems participated in a short psychoacoustical study where each of the six experimental stimuli were adjusted in loudness to equal the loudness of a seventh stimulus (i.e., method of adjustment). The subject mix was equivalent to that utilized in Preliminary Experiment 1. Each subject adjusted the sound level of each of the six stimuli (comparison stimuli) until each was perceived to be equal in loudness to a test stimulus (i.e., practice session sound) presented at the metered 76 dB(A) (SLM set on SLOW response) determined from the prior pre-experiment. The background was again presented at 72 dB(A) during this experiment. For each comparison, both the comparison stimulus (i.e., comparison stimuli tested one at a time) and the test stimulus were played one after the other. Each sound was presented for approximately 2 seconds with a pause of approximately 1 second between the test and comparison sound. The subject was able to increase and decrease the level of the comparison stimulus using two separate keys on a computer keyboard. The sounds were alternately repeated until the subject indicated that the two sounds had been adjusted to equal one another in loudness.

After the sound had been adjusted to equal the test stimulus, a pink noise was played in place of the comparison and test sound at the adjusted levels and a pink noise reference level was recorded. Although the level of the test sound was not manipulated, the pink noise was measured at the test sound presentation level for calibration purposes. The relative difference in pink noise levels for each of the seven stimuli was used to adjust the loudness of the sounds in the main experiment. The respective dB(A) levels for each stimulus that represented the necessary level to maintain equal subjective loudness across the seven stimuli appear in TABLE 2-8.

TABLE 2-8

Required dB(A) level to maintain equal subjective loudness across stimuli

Stimulus	dB(A)
Low-Fuel Warning	75.7
Radio Shack Buzzer	79.1
Repeating Pattern	73.5
Male Digitized	77.7
Female Digitized	78.6
Male Synthesized	81.5
Practice Session Stimulus	75.9

2.7 EXPERIMENTAL PROCEDURES

Prior to the experiment date, each subject underwent a two step screening procedure that began with a phone call screening to determine subject eligibility. Participants were screened for age, gender, and driving status in order to fulfill the experimental design requirements. Each subject was required to hold a current driver's license and drive on a regular basis. The driver's license was also used to verify the age of each subject. Eligible subjects were then scheduled to perform an audiometric hearing test, and subjects who passed the hearing test were then admitted into the study.

During each two-hour data collection session, the subject received an informed consent overview, an instructional and training segment, that included joystick calibration and practice experimental conditions, a three part data collection phase with rest breaks, and a debriefing and payment session.

2.7.1 Participant Audiogram Screening

In addition to the phone call screening requirements, the hearing of these individuals was tested, prior to the actual experiment date, using an audiometric hearing test procedure. The hearing test procedures and criteria to be met in order to participate in the study are described in this section

This test was conducted at the subject's place of residence using a Teledyne Avionics TA-20 computer controlled audiometer. The quietest room in the subject's house was used as the testing area Therefore, hearing thresholds (dBHL) may have been affected by ambient noise within the home, especially at the lower frequencies where the ear muff did not provide sufficient noise attenuation. Corrective hearing devices were not allowed to be worn during the hearing test or during the experiment.

The hearing criteria for participation in the study was selected using the hearing threshold graphs for a large international sample of persons not exposed to occupational noise (Spoor, 1967). Liberal criteria was chosen such that a minimal number of subjects would be excluded while still eliminating subjects with pronounced hearing loss. The dBHL criteria required at each frequency were calculated using the graph for males as a reference. This graph was selected since an analysis of the audiograms of the four subject groups (i.e., two age groups, male and female subgroups) indicated that the audiograms for the female participants tested in each age group matched the graph for males more closely than the graph for females. A separate method was used to determine the criteria for each age group. Bilateral hearing differences at each frequency for each age group were limited to 30 d.B

Under 45 Age Group Hearing Criteria For the under 40 age group, a 15 dBHL measurement was the maximum allowable hearing threshold level at each of the pure tone test frequencies above 1000 Hz. This was selected by using the 8000 Hz curve and determining the associated value on the ordinate axis with the 40 Age In Years point on the abscissa and then rounding to the nearest 5 dB increment. The 8000 Hz curve was selected because of the small range in dBHLs across frequencies at that age, while the rounding upwards was performed to compensate for the uncontrolled testing environment. In addition to the rounding at higher frequencies, a 25,20 and 20 dBHL were allowed at the 250,500, and 1000 Hz test frequencies, respectively, because of noticeable noise in some test environments that could not be abated (e.g., refrigerator noise, highways, and HVAC systems). This additional hearing threshold increase of 10,5, and 5 dB, at the 250,500, and 1000 Hz test frequencies, respectively, was also applied to the 65 and over age group hearing criteria discussed below.

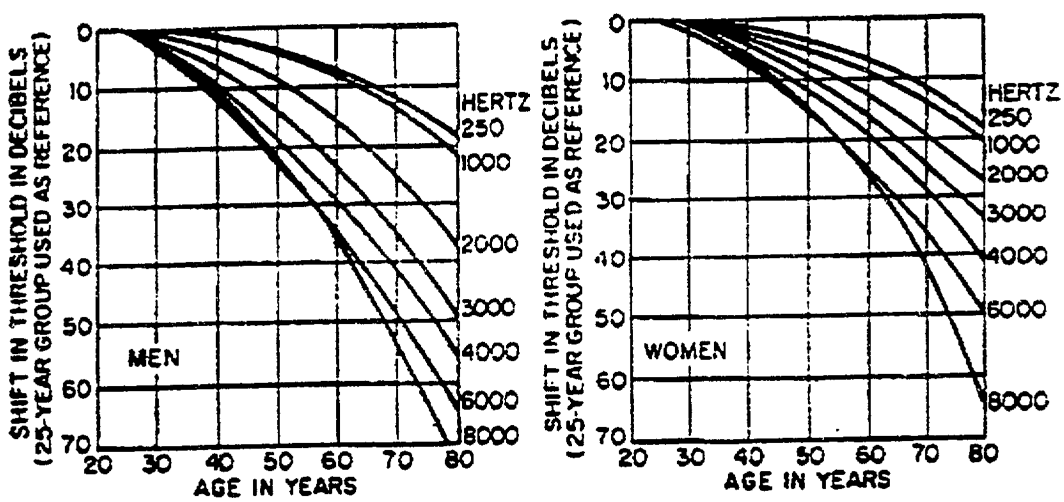


Figure 2-26. Hearing dependence on age (presbycusis). Median hearing level of large international sample of persons not exposed to occupational noise. All hearing levels relative to 25-year-olds with normal hearing (Spoor, 1967)

65 and Over Age Group Hearing Criteria. Hearing criteria for the 65 and over age group were determined for each of the 7 pure tone test frequencies and for 2 age ranges within the group. The two age ranges were 65-69 and 70 and over. Two age ranges were necessary due to the age distribution of the older subjects, and the resulting difference in expected hearing performance between the subjects.

The hearing thresholds at each frequency for each age range were determined using the 70 Age In Years point on the abscissa for the 65-69 age range, and the 80 Age In Years point for the 70 and over range. A 10 dB compensation factor was then added to the respective dBHL level for each frequency curve to account for the testing environment and the need to create a somewhat liberal criteria for the reasons stated above. The additional hearing threshold increase, as applied in the younger age group hearing criteria, was also applied. The resulting hearing threshold criteria used during subject screening appears in TABLE 2-9.

Results. The hearing threshold level curves for each gender in each age group were calculated by taking the average hearing threshold for subjects' better ears at each test frequency across all subjects within each age group. The two respective curves for each age group appear in Figure 2-27.

Only one of the 24 subjects had a bilateral hearing sensitivity difference at any test frequency above 20 dB at 25 dB. Two subjects were inadvertently admitted into the study who did not meet the hearing criteria. These subjects, however, were assumed to have normal hearing and their data were retained in the analysis based on several observations. For a 66 year old male subject, his hearing performance easily passed the 70's age group hearing criteria, but failed the 60's criteria at the 2000,3000, and 6000 Hz test frequencies by 5,10 and 15 dB respectively. For a 29 year old female subject, performance on the better ear and bilateral hearing sensitivity performance passed the hearing criteria for the younger age group, even though one ear failed the hearing criteria. These two subjects were retained since their hearing performance did not indicate pronounced hearing loss that warranted the removal of

TABLE 2-9

Hearing Threshold Level (dBHL) Criteria for each frequency in any ear (relative to audiometric zero) and maximum bilateral hearing differences at each frequency.

	Age		
Frequency	≤45	60’s	70’S
250	25	35	40
500	20	30	35
1000	20	30	35
2000	15	35	45
3000	15	45	55
4000	15	50	65
6000	15	55	75
8000	15	60	80
max L-R difference	30	30	30

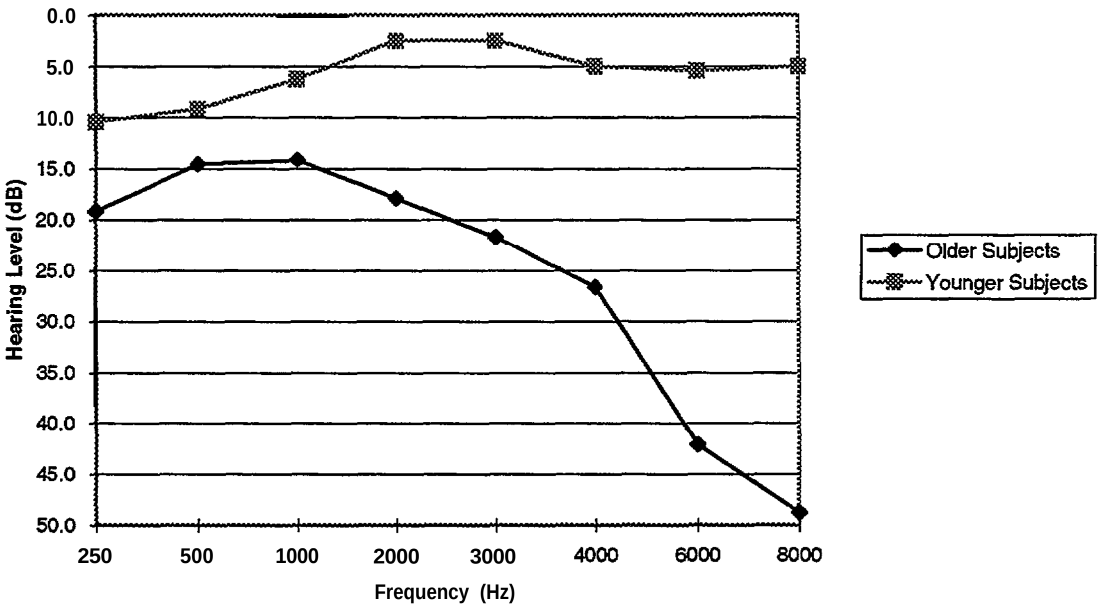


Figure 2-2 7. Mean pure-tone hearing levels for subjects' better ears (12 per group).

two additional subjects in order to maintain equal sample size within cells. One additional subject failed the hearing criteria at the 500 Hz test frequency for one ear by 5 dB, but was allowed to participate in the study due to the limited number of participants in the mature subject pool The data for the audiometric hearing testing procedure appear in APPENDIX B in two tables created by age group and sorted by gender. Audiogram data points that failed the specified hearing criteria are indicated by asterix.

2.7.2 Instruction and Training

Subjects allowed to participate in the study were required to read and sign an informed consent form once they arrived for the experiment. A sample of this form appears in APPENDIX C. The experimenter described the necessary tasks the subject would be required to perform during the experiment. This was accomplished in verbal form, where the experimenter reviewed the instructions with the subject (verbal instructions given to the subject appear in APPENDIX D). The subject was first seated in the vehicle and the proper seating position was attained before the instruction and training was started. The subject was then familiarized with the localization and bridge-spotting tasks, input devices, and appropriate method of providing responses. Following the verbal instructional phrase, and after the subject had the opportunity to ask questions, the practice session was started that included joystick calibration and practice experimental trials

2.7.3 *Practice Session*

JoystickCalibration. Since the joystick axis was not concentric with the subject's head, there was discrepancy between the subject's perceived location of the sound and the direction in which the joystick was pushed. To account for this measurement error, each subject was asked to push the joystick in several pre-determined directions to anchor the coordinates of the joystick at several points. These anchor points were then used during data reduction and transformation to determine the actual subject response relative to the vehicle coordinate system. For calibration, each subject was asked to push the joystick towards twelve designated points within the vehicle. These twelve points appear in TABLE 2-10.

Each direction was calibrated three times (not including the practice session calibration) during the experiment and an average of these measurements was taken for each anchor point for use with that subject's raw data. The calibration procedure was performed several times throughout the experiment to account for joystick input variability as a result of increasing familiarity with the task and input device.

Practice Experimental Conditions. After the calibration procedure, the subject was presented with simulated experimental trials, the secondary task, and the background noise. For this session, a single stimulus (Refer to Stimulus section) was presented from each speaker activation mode once for a total of 16 practice treatments. The subject was asked to respond by pushing the joystick in the direction of the sound and then to press the button once the desired direction of the joystick matched the perceived location of the sound. The subjects were instructed to respond as quickly and as accurately as possible once they had determined the location of a sound. The secondary task was also performed during this portion of the practice session. The subject was allowed to ask questions during the practice session. The driver's door was left open during the practices session to facilitate answers to subjects' questions, but was closed during data collection.

2.7.4 Experimental Trials and Secondary Task

Once the practice session had been completed and the subject was comfortable with the required tasks, the subject was given a short l-2 minute break. The subject then proceeded with the first calibration routine and continued immediately into the first data collection block of 96 trials. After the first data collection block, a 5 minute break was given. The second and third data collection blocks followed the same procedure; however, debriefing and payment followed directly after the third data set. The subject was instructed to not ask questions during the experiment unless there were problems or if they wished to withdraw from the study.

TABLE 2-10

Twelve calibration directions within the vehicle

Calibration	Specific Direction Instructed
1	the left edge of the windshield
2	directly in front of you
3	the center of the windshield
4	the right edge of the windshield
5	directly to your right
6	the center of the right rear door
7	your right blindspot
8	the center of the rear window
9	directly behind you
10	your left blindspot
11	the center of the left rear door
12	directly to your left

The timing of the stimulus presentations were both subject and computer paced. The presentation of the stimulus was terminated as soon as a response was registered. At this point, the next condition was presented randomly within a 6 second window beginning 4 seconds after the last response. Consequently, the proximity of stimulus presentations ranged from about 4 to 10 seconds. This presentation window helped prevent the subject from timing when the stimulus would be presented. In no instance was the subject ever prompted by the experimenter to make a response.

The subjects were told that identifying 75% of the total number of bridges that appeared along the video taped route would earn them a bonus of $5. The TV monitor for this task was mounted over the hood of the vehicle, thus requiring the subject to maintain a gaze through the front windshield. This task was included primarily to encourage the subject to maintain a relatively fixed head position during stimulus presentation and throughout the experiment. However, it also provided additional workload and presented the subject from devoting full attention to the localization task The average number of bridges spotted during each of the three data collection segments were 23,15, and 26 respectively. Each data collection segment was approximately 20-25 minutes in length.

The entire experiment lasted approximately 1 hour 45 minutes.

2.7.5 Subject Debriefing and Payment

The study provided subjects with a $45 (including bonus) payment for participation. The $5.00 bonus was paid regardless of the subject's performance on the bridge spotting task However, all subjects performed acceptably on the secondary task The main purpose of the bridge-spotting task (i.e., maintaining head position) was withheld from participants until debriefing, and then was only explained if necessary.

3.0 RESULTS

Four 3-way mixed factorial ANOVA procedures were conducted in order to analyze the four dependent measures of response time, decision time, accuracy, and azimuth. . Each of these ANOVA designs were identical with the only difference being the dependent measure analyzed. The three factors manipulated were Speaker (16 levels), Sound (6 levels) and Age (2 levels). Age was nested within subjects, while Speaker and Sound were within-subjects variables. Each subject underwent three replications of 96 unique conditions for a total of 288 experimental conditions (refer to section entitled ***Experimental Design*** for complete details of the factorial experiment).

Since the experimental design included within-subject variables, the Greenhouse-Geisser correction was applied to ensure that the sphericity assumption of homogeneity of covariance for repeated measures was not violated--violation of this assumption can bias the **ANOVA** test in the positive direction. The Greenhouse-Geisser $\in$ factor adjusts the degrees of freedom based on the actual amount of heterogeneity present in the experiment, thus preventing the test from becoming negatively biased, as might be the case when the conservative Greenhouse-Geisser correction is used which ***assumes*** maximal heterogeneity (**Winer**, Brown and **Michels**, 1991; Keppel, 1991). Analyses were conducted using the SAS System for Windows and the **SuperANOVA** statistical analysis package for the Macintosh

The results of the **ANOVA** procedures for each of the four dependent measures are discussed separately. Data reduction performed for each measure prior to the analysis is described first, followed by the results of the overall analysis. Significant main effects and interactions are then discussed in detail and conclusions derived.

Since the presence of interactions involving significant interacting main effects complicates the interpretation of the main effects alone, only non-interacting significant main effects are discussed in addition to the interactions. This applies to higher order interactions, as well, where the analysis of a three way interaction must take precedence over interacting main effects and two-way interactions. Exceptions to this rule are made, however, when an analysis of an interaction can be simplified through inspection of an interacting main effect. This will occur when the choice of the simple-effects to analyze using the simple-effects F-test requires an understanding of an interacting main effect to replace the partially redundant information forfeited by disregarding the complimentary set of simple-effects. For example, for a significant Speaker-by-Sound interaction, the simple effects of Sound at each level of Speaker could be analyzed instead of the simple effects of Speaker at each level of Sound. The main effect of Speaker could then be subjected to post-hoc tests in order to further explain the interaction. This method allows the most meaningful simple-effects to be thoroughly investigated without forfeiting any information. Significant interacting main effects and interactions are also discussed when they aid in drawing overall conclusions for the ANOVA procedure.

3.1 RESPONSE TIME

3.1.1 Data Reduction

The response times for the each of the 96 treatment conditions were attained by averaging the response times across the three replications for each condition. Missing values were substituted by the mean of the remaining two times. Missing values occurred for 23 of the 6912 (288 x 24) conditions; however, no more than 1 of the 288 conditions for each subject was lost for any one subject. Since four dependent measures were recorded for each condition, missing values were also substituted in the same fashion for the other three dependent measures (i.e., decision time, accuracy and azimuth).

3.1.2 Overall Analysis

TABLE 3-l contains the ANOVA summary table for the response time dependent measure. Using the Greenhouse-Geisser correction where appropriate, the main effects of Age {F(1,22)=11.28O,p=0.0028), Sound {F(5,110)=7.083,p=0.0010}, and

TABLE 3- 1

ANOVA Summary Table for Response Time

Source	*df*	MS	*F*	*p*	*G-G E*	*G-Gp*
Between-Subiects						
Age	1	135.024	11.280	0.0028		
Subjects(Age)	22	11.970				
Within-Subiects						
Sound	5	6.365	7.083	< 0.0001	0.486	0.0010
Sound x Age	5	0.908	5.050	0.0003	0.486	0.0064
Sound x Subjects(Age)	110	0.180				
Speaker	15	3.067	18.661	< 0.0001	0.344	< 0.0001
Speaker x Age	15	0.164	0.996	0.4587	0.344	0.4249
Speaker x Subjects(Age)	330	0.164				
Sound x Speaker	75	0.146	2.161	< 0.0001	0.153	0.0156
Sound x Speaker x Age	75	0.080	1.180	0.1434	0.153	0.2998
Sound x Speaker x Subjects(Age)	1650	0.068				
Total	2303					

Speaker {F(15,330)=18.661, p<0.000l }, and the interactions of Sound-by-Age {F(5,110)=5.050,p=0.0064} and Sound-by-Speaker {F(75,1650)=2.161,p=0.0156} were found to be significant at the p<0.05 alpha level. No other interactions were found to be significant at the specified alpha level.

3.1.3 Sound-by-Age Interaction

A simple-effects F-test was conducted on the Sound-by-Age interaction to determine the sources of the interaction, An analysis of the simple-effects of Sound at each level of Age and of Age at each level of Sound was performed. The ANOVA summary tables for these simple-effects F-tests appear in TABLE 3-2 and TABLE 3-3. The results indicated that all levels of both variables were significantly different at all levels of the other variable. That is, both age groups responded at significantly different speeds for each sound, and Sound was significant at each level of Age. A Newman-Keuls test was then conducted on the significant simple-effects for Sound to determine significant differences between the levels of sound at each age level. Since Age had but two levels, no post-hoc analysis was necessary. The results of the Newman-Keuls test are incorporated with a graph illustrating the Sound-by-Age interaction in Figure 3-1.

Sounds labeled with the same letter were not found to be significantly different from one another at the p<0.05 level of significance. For the older subjects, response time was significantly slower, by about 0.15 to 0.20 s, for Sound 2 (buzzer) and Sound 3 (repeating pattern), while the younger subjects responded to Sound 1 (low-fuel warning) significantly faster, by about 0.13 to 0.16 s, than the other sounds. Across the various sounds, the response times between the two age groups varied from 0.36 to 0.57 s.

TABLE 3-2

Simple-Effects F-Test Results for Sound at each level of Age for Response Time.

Age	MS	*F*	*P*	*G-G e*	*G-Gp*
Young	0.722	4.008	0.0022	0.486	0.0120
Old	1.459	8.105	< 0.0001	0.486	0.0001

Note: ***All p-***values were calculated using df_{num}=5 and df_{den}=110.

All F-ratios were calculated using the MSE=0.180.

TABLE 3-3

Simple-Effects F-test Results for Age at each Level of Sound for Response Time

Sound	MS	***F***	***p***	***G-G e***	***G-G p***
Low Fuel (1)	31.988	177.712	< 0.0001	0.486	< 0.0001
Buzzer (2)	30.290	168.280	< 0.0001	0.486	< 0.0001
Pattern (3)	31.623	175.682	< 0.0001	0.486	< 0.0001
Male Dig. (4)	16.096	89.421	< 0.0001	0.486	< 0.0001
Female Dig. (5)	16.981	94.340	< 0.0001	0.486	< 0.0001
Male Syn. (6)	12.583	69.908	< 0.0001	0.486	< 0.0001

Note: All *p*-values were calculated using df_{num}=1 and df_{den}=110.
All F-ratios were calculated using the MSE=O. 180.

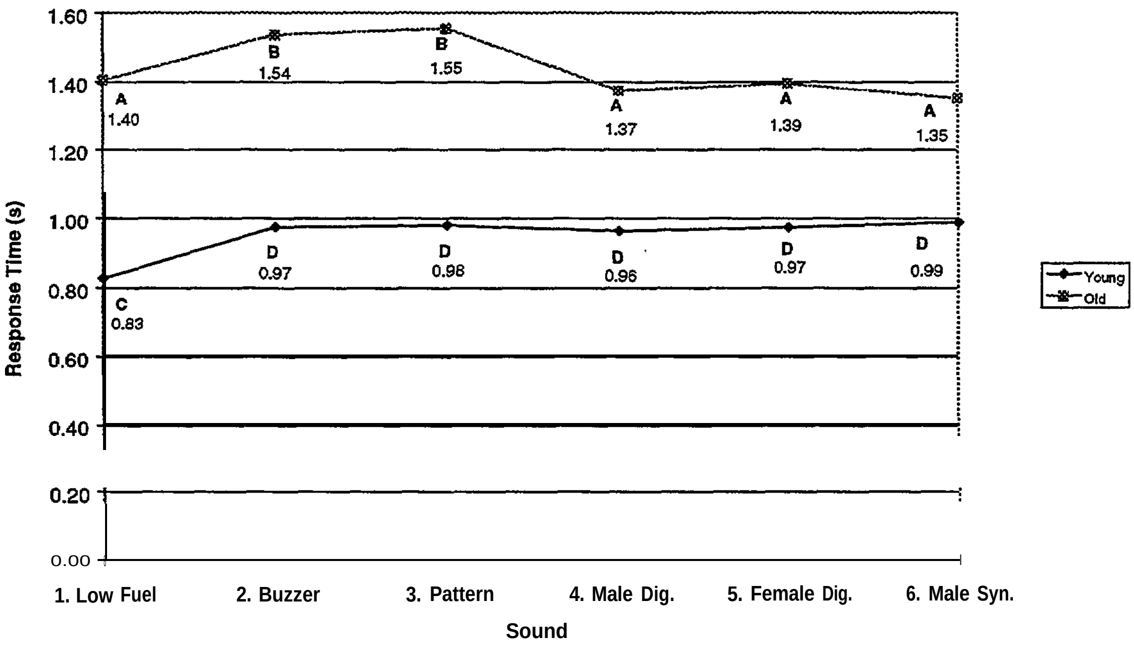


Figure 3-1 Sound-by-Age interaction for Response Time. Sounds labeled with the same letter were not found to be significantly different from one another at thepc0.05 level of significance.

3.1.4 Sound-by-Speaker Interaction

Simple-effects F-tests were also conducted on the Sound-by-Speaker interaction to identify sources of the interaction. An analysis of the set of simple-effects for Sound at each level of Speaker was performed. The simple-effects of Speaker at each level of Sound were not investigated. Instead, the main effect of Speaker was analyzed as a substitute to simplify the analysis and presentation of the interaction. The ANOVA summary table for the simple-effects F-tests for Sound at each level of Speaker appears in TABLE 3-4.

The results indicated that the simple-effects of Sound were significant at 8 of the 16 speaker levels A Newman-Keuls test was conducted on each of these significant simple-effects for Sound to determine significant dlfferences between the levels of Sound for these speakers. Figure 3-2 illustrates the interaction combined with Newman-Keuls results labeled for significant simple-effects of Sound at the respective speaker locations. Sounds that performed significantly different from the group are labeled separately, while groups of sounds that performed similarly are circled. In addition, the lettering convention used to identify groups of similarly performing sounds is also utilized.

The Newman-Keuls test results for the significant simple-effects of Sound at Speaker conditions 5,10,11,12,14,15, and 16 indicate a strong speaker interaction with the repeating pattern and buzzer (Sounds 2 & 3) acoustic warnings. In these cases, at least one of these two sounds were responded to significantly slower than the rest of the group. For the Speaker 13 and 15 conditions, however, the voice warnings tended to perform worse as a group and Sound 3 performed on equal grounds with Sound 1.

General observation of the plotted interaction indicates that voice warnings as a group usually outperformed the acoustic warning group at each speaker condition; However, voice warnings tended to perform poorer as a group at the Speaker 13 and 15 conditions. It is also evident that the combination speaker levels (i.e., 13 through 16) tended to result in significant sound interactions. Since no simple-effects were found for

TABLE 3-4

Simple Effects of Sound at Each Level of Speaker for Response Time

Speaker	MS	*F*	*p*	***G-G e***	***G-Gp***
1	0.135	1.985	0.0079	0.153	0.1166
2	0.093	1.365	0.2346		
3	0.091	1.342	0.2438		
4	0.032	0.467	0.8014		
5	0.245	3.610	0.0030	0.153	0.0139
6	0.157	2.308	0.0421	0.153	0.0770
7	0.136	2.007	0.0749		
8	0.063	0.922	0.4655		
9	0.063	0.920	0.4669		
10	0.458	6.728	< 0.0001	0.153	0.0002
11	0.45 1	6.626	< 0.0001	0.153	0.0003
12	0.185	2.722	0.0186	0.153	0.0449
13	0.608	8.937	< 0.0001	0.153	< 0.0001
14	0.214	3.143	0.0079	0.153	0.0258
15	0.189	2.779	0.0166	0.153	0.0417
16	0.348	5.124	0.0001	0.153	0.0019

Note: All *p*-values were calculated using $df_{num}=5$ and $df_{den}=1650$.

All F-ratios were calculated ***using the*** MSE=0.068.

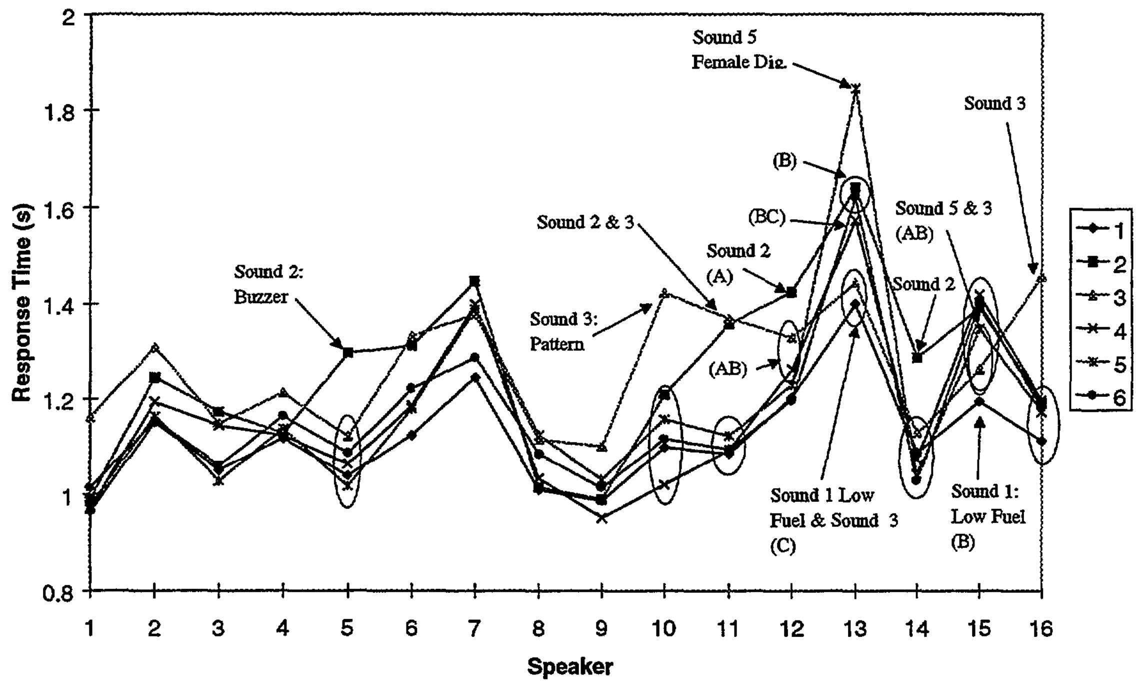


Figure 3-2. Sound-by-Speaker interaction for Response Time. Newman-Keuls results labeled for significant simple-effects of Sound.

the remaining speaker levels, the analysis proceeded to the Speaker main effect to complete the analysis of the Speaker-by-Sound interaction.

3.1.5 Speaker Main Effect

The significant main effect of Speaker was analyzed using the Newman-Keuls procedure. The results of this procedure appear in TABLE 3-5. Since many speaker levels interacted with sound, the results of the Sound-by-Speaker analysis must be considered with the Speaker main effect results discussed here.

From the Newman-Keuls results, it appears that the best performing speakers were those that did not interact with sound. Speakers 1,3,4,5,8,9 and 14 were among the speakers responded to the fastest. Despite the poor performance of Sound 2 at Speaker 5 and 14, these speakers still petiormed extremely well This supports the observation that Sounds 2 and 3 petiormed less well ***overall.*** At the extremes, Speakers 1 and 9 situated on the left A-pillar performed the best, while the Speaker 13 combination (i.e., both A-pillars) performed the worst.

Furthermore, response time was fastest for speakers located on the left (both speakers) and right (top speaker) A-pillars, left and right B-pillars, and on the right A- and C- pillar combination. These speakers were either in front of or directly to the left or right of the subject. The speaker combinations as a group were responded to slower, as were speakers located behind the driver. The locations of the speakers are included in TABLE 3-5 in the column labeled ***Location*** as Left, Right, Front-L, Front-R, Rear-L and Rex-R (i.e., -L and -R designate left or right corners for the front and rear). The poorer performance of the Speaker 2 condition is notable since its position, centered with the windshield and above the rear-view mirror, is considered a likely location for an alarm housing. It also was slowest to respond to for speakers located in-front of the driver. The poorer performance of the Speaker 13 condition is also notable since even though the speakers used for this combination ranked high independently, combined they performed worse than any other speaker condition.

TABLE 3-5

Newman-Keuk Results for Speaker Main Effect for Response Time

Mean (s)	Speaker	Location	Newman-Keuls Grouping
1.0111	9	Front-L	A
1.0117	1	Front-L	A
1.0627	8	Left	A B
1.1002	3	Front-R	A B C
1.1030	5	Rear-R	A B C
1.1070	14	Right	A B C
1.1460	4	Right	A B C D
1.1690	10	Front-R	B C D
1.1861	11	Rear-R	B C D
1.2023	2	Front	B C D E
1.2180	16	Left	C D E
1.2249	6	Rear	C D E
1.2733	12	Rear-L	D E F
1.3350	15	Rear	E F
1.3562	7	Rear-R	F
1.5863	13	Front	G

Note: Means with the same letter are not significantly different at p=0.05.
MSE = 0.164, ***df* =** 330 Finally, with the exception of the Speaker 13 and 15

Finally, with the exception of the speaker 13 and 15 conditions, the significant simple-effects appeared to have been influenced by the poor performance of Sounds 2 and 3. However, although the simple-effects of Sound for the other speaker levels were not significant at $p<0.05$, through inspection of Figure 3-2 it is evident that Sounds 2 and 3 performed poorly overall.

3.2 *DECISION TIME*

Data Reduction. The decision times for the each of the 96 treatment conditions were attained by averaging the decision times across the three replications for each condition Missing values were substituted by the mean of the remaining two times as discussed previously.

3.2.1 Overall Analysis

TABLE 3-6 contains the ANOVA summary table for the decision time dependent measure. Using the Greenhouse-Geisser correction where appropriate, the main effects of Sound $\{F(5,110)=9.074, p=0.0001\}$ and Speaker $\{F(15,330)=13.099, p<0.0001\}$, and the interactions of Sound-by-Age $\{F(5,110)=4.747, p=0.0078\}$ and Sound-by-Speaker $\{F(75,1650)=2.217, p=0.0178\}$ were found to be significant at the $p<0.05$ alpha 1evel. No other interactions were found to be significant at the $p<0.05$ alpha Ievel.

3.2.2 Sound-by-Age Interaction

The simple-effects F-test was conducted on the Sound-by-Age interaction An analysis of the simple-effects of Sound at each level of Age and of Age at each level of Sound was performed. The ANOVA summary tables for these simple-effects F-tests appear in TABLE 3-7 and TABLE 3-8.

The results indicated that all levels of both variables were significantly different at all levels of the other variable. That is, both age groups made their localization decision at significantly different speeds for each sound, and Sound was significant at

TABLE 3-6

ANOVA Summary Table for Decision Time.

Source	***df***	***MS***	***F***	***p***	***G-G e***	***G-Gp***
Between-Subiects						
Age	1	141.643	2.499	0.1282		
Subjects(Age)	22	56.672				
Within-Subiects						
Sound	5	2.369	9.074	< 0.0001	0.504	< 0.0001
Sound x Age	5	1.240	4.747	0.0006	0.504	0.0078
Sound x Subjects(Age)	110	0.261				
Speaker	15	4.525	13.099	< 0.0001	0.367	< 0.0001
Speaker x Age	15	0.237	0.687	0.7978	0.367	0.6481
Speaker x Subjects(Age)	330	0.345				
Sound x Speaker	75	0.257	2.217	0.0001	0.133	0.0178
Sound x Speaker x Age	75	0.146	1.254	0.0730	0.133	0.2581
Sound x Speaker x Subjects(Age)	1650	0.116				
Total	2303					

TABLE 3-7

Simple-Effects F-test for Sound at each level of Age for Decision Time

Age	MS	*F*	*p*	**G-G e**	***G-Gp***
Young	1.173	4.49465	0.0009	0.504	0.0089
Old	2.436	9.3333	<0.0001	0.504	0.0001

Note: All *p*-values were calculated using $df_{num}=5$ and $df_{den}=110$.
All F-ratios were calculated using the MSE= 0.261

TABLE 3-8

Simple-Effects F-test for Age at each level of Sound for Decision Time

Sound	MS	***F***	***P***	***G-G e***	***G-Gp***
Low Fuel (1)	39.941	153.030	< 0.0001	0.486	< 0.0001
Buzzer (2)	30.221	115.789	< 0.0001	0.486	< 0.0001
Pattern (3)	32.622	124.988	< 0.0001	0.486	< 0.0001
Male Dig. (4)	15.648	59.955	< 0.0001	0.486	< 0.0001
Female Dig. (5)	14.101	54.026	< 0.0001	0.486	< 0.0001
Male Syn. (6)	15.309	58.654	< 0.0001	0.486	< 0.0001

Note: ***All p-values*** were calculated using df_{num}=l and df_{den}=110.
All F-ratios were calculated using the MSE-0.261.

each level of Age. A Newman-Keuls test was then conducted on the significant simple-effects for Sound to determine significant differences between the levels of Sound at each Age level. Since Age had but two levels, no post-hoc analysis was necessary. The results of the Newman-Keuls test are incorporated with a graph illustrating the Age-by-Sound interaction in Figure 3-3. Sounds labeled with the same letter were not found to be significantly different from one another at the $p<0.005$ level of significance.

The results of the decision time analysis reveal a similar trend in sound performance as found with response time. For the older subjects, decision time was significantly slower for the buzzer and repeating pattern sounds, and the younger subjects again responded to the low-fuel warning stimulus significantly faster than the other sounds. The decision times were approximately 0.8 s longer than the response times for both age groups and all sounds.

3.2.3 Sound-by-Speaker Interaction

A simple-effects F-test was conducted on the Sound-by-Speaker interaction for decision time to determine the sources of the interaction. An analysis of the simple-effects of Sound at each level of Speaker was performed. The ANOVA summary tables for these simple-effects F-tests appear in TABLE 3-9.

The results of the simple-effects F-tests indicated that the simple-effects of Sound were significant at 5 of the 16 speaker levels. A Newman-Keuls test was conducted on each of the significant simple-effects for Sound to determine significant differences between the levels of Sound at each Speaker level. The results of the Newman-Keuls tests are incorporated in Figure 3-4. Sounds that differed significantly from the group are labeled, while the remaining members of the group that did not significantly differ from one another are circled.

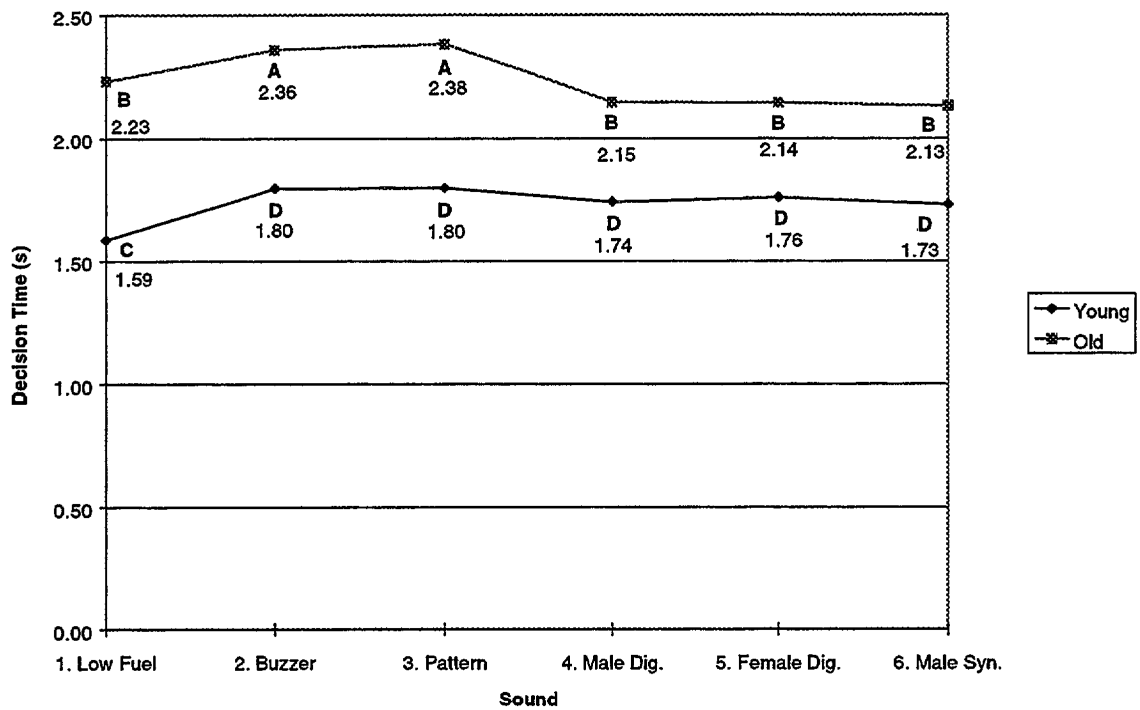


Figure 3-3. Sound-by-Age interaction for Decision Time. Sounds labeled with the same letter were not found to be significantly different from one another at the p<0.05 level of significance.

TABLE 3-9

Simple Effects of Sound at Each Level of Speaker for Decision Time

Speaker	MS	*F*	*P*	*G-G e*	*G-Gp*
1	0.213	1.8359	0.1028		
2	0.152	1.3112	0.2565		
3	0.207	1.7880	0.1121		
4	0.236	2.0338	0.0712		
5	0.290	2.5000	0.029	0.133	0.1153
6	0.139	1.2006	0.3065		
7	0.122	1.0543	0.3841		
8	0.115	0.9950	0.4193		
9	0.068	0.5861	0.7107		
10	0.641	5.5289	< 0.0001	0.133	0.0196
11	1.009	8.6948	< 0.0001	0.133	0.0035
12	0.426	3.6701	0.0026	0.133	0.0567
13	0.828	7.1341	< 0.0001	0.133	0.008 1
14	0.501	4.3 194	0.0007	0.133	0.0388
15	0.250	2.1575	0.0563		
16	1.030	8.8816	< 0.0001	0.133	0.0032

Note: All *p*-values were calculated using df_{num}=5 and df_{den}=1650.

All F-ratios were calculated using the MSE=O. 116.

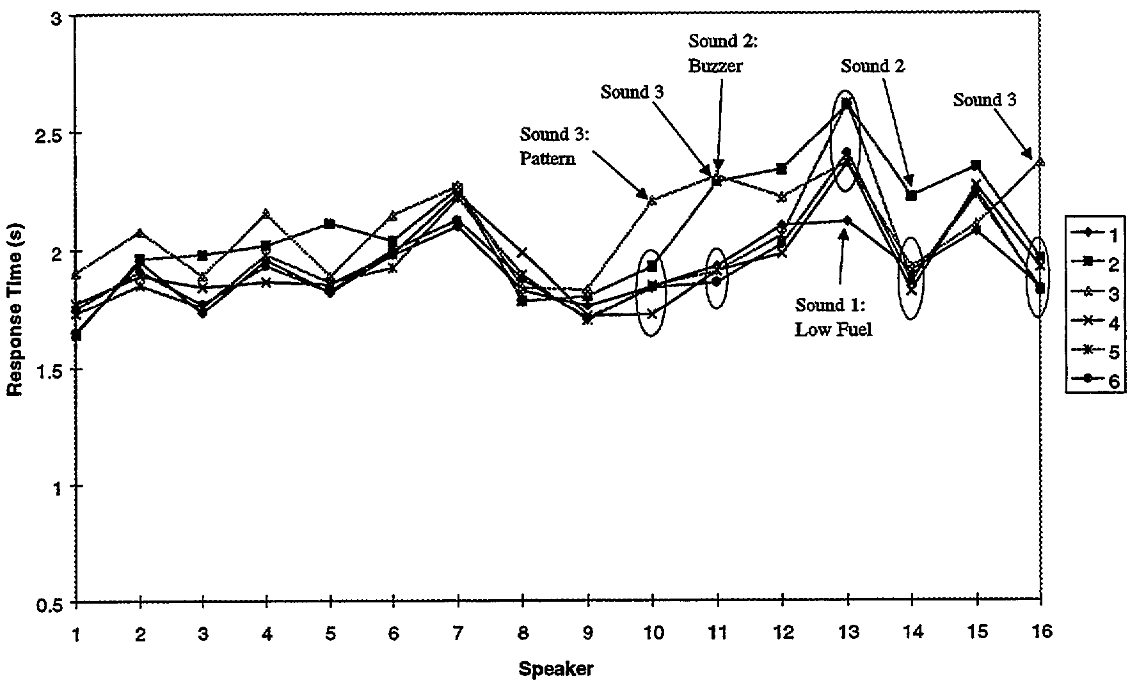


Figure 3-4. Sound-by-Speaker interaction for Response Time. Newman-Keuls results labeled for significant simple-effects of Sound.

The results are similar to those found with the response time analysis. Poorer performance of Sound 2 and 3 resulted in simple-effects at several speaker conditions and was the primary cause of the Sound-by-Speaker interaction With the exception of Speaker 13, these sounds performed significantly worse than the rest of the sounds. The difficulty in localizing the sounds using Speaker 13 is again evident; However, Sound 1 significantly outperformed the group at this location, scoring nearer to the average for the remaining speaker conditions.

3.2.4 Speaker Main Effect

A Newman-Keuls test was performed on the Speaker maiu effect from the overall analysis and the results appear in TABLE 3-10. Once again care must be taken in interpreting these results, since the Speaker-by-Sound interaction is present. The test, however, does provide a general ranking of the speakers based on overall performance with the six sounds. The results of the Newman-Keuls test are similar to those found for response time: Speakers 1 and 9 performed best, Speaker 13 performed worst, and speakers in front or directly to the left or right of the subject performed better as a group than speakers located behind the subject. Overall, there were less significant differences in decision time between the speaker conditions than there were for response time. This is evident by the number of Newman-Keuls groupings generated for each analysis. A notable difference between the response time and decision time Newman-Keuls test results for the Speaker main effect is the inclusion of the Speaker 2,10 and 16 conditions into the fastest ranked group when performance is based on decision time.

TABLE 3-10

Newman-Keuls Test on the Speaker Main Effect for Decision Time

Mean (s)	Speaker	Location	Newman-Keuls Grouping
1.7417	1	Front-L	A
1.7527	9	Front-L	A
1.0272	3	Front-R	A B
1.8652	8	Left	A B
1.8903	5	Rear-R	A B
1.8951	10	Front-R	A B
1.9327	14	Right	A B C
1.9375	2	Front	A B C
1.9527	16	Left	A B C
1.9814	4	Right	B C
2.0080	6	Rear	B C
2.0300	11	Rear-R	B C
2.1165	12	Rear-L	C D
2.1979	7	Rear-R	D
2.2099	15	Rear	D
2.4094	13	Front	E

Note: Speakers with the same letter are not significantly different ($p<0.05$).
Calculations based on MSE=0.l16 and df=1650.

3.3 ACCURACY

3.3.1 Data Reduction

The x- and y-coordinates of all joystick positions recorded during the experiment were transformed to an azimuth direction where a 0^o azimuth corresponded to a direction of the joystick that was anchored at directly in front of the subject's head and a 90^o azimuth corresponded to a direction that was anchored directly to the right of the subject. Transformation of the x- and y-coordinates to an azimuth direction involved mapping the passenger compartment relative to the 12 anchor points collected during joystick calibration, and then determining where each response fell within the coordinate space.

Since no two subjects assigned exactly the same coordinate points for each of the 12 anchor points requested, a unique mapping of the passenger compartment was performed for each of the 24 subjects. The twelve anchor points recorded during each of the 3 calibration sessions were averaged for each subject and were then mapped to the passenger compartment. This procedure ensured that variations in joystick positioning for the same desired direction across subjects was minimized.

Each of the 288 x- and y-coordinate pairs for each subject were then converted into an azimuth and their absolute deviation in degrees from the correct speaker azimuth determined the accuracy of the response. Deviations were averaged across the three replications for each of the 96 conditions and the average was used as the dependent measure for the 3-way ANOVA Descriptions of the twelve anchor points appear in TABLE 3-10, while azimuths corresponding to the stimulus speakers appear in the TABLE 2-5 for reference.

3.3.2 Overall Analysis

TABLE 3-l 1 contains the ANOVA summary table for the accuracy dependent measure. Using the Greenhouse-Geisser correction where appropriate, the main effects of Sound {$F(5,110)=7.141$, $p=0.0002$} and Speaker {$F(15,330)=16.071$, $p<0.0001$}, and the interactions of Sound-by-Speaker {$F(75,1650)=2.379$, $p=0.0042$} and Sound-by-Speaker-

TABLE 3-11

ANOVA Summary Table for Accuracy

Source	*df*	MS	*F*	*P*	*G-G e*	*G-Gp*
<u>Between-Subjects</u>						
Age	1	16466.349	1.695	0.2064		
Subjects(Age)	22	9713.322				
<u>Within-Subjects</u>						
Sound	5	1915.945	7.141	< 0.0001	0.641	0.0001
Sound x Age	5	446.647	1.665	0.1491	0.641	0.1794
Sound x Subjects(Age)	110	268.314				
Speaker	15	24025.089	16.071	< 0.0001	0.282	<0.0001
Speaker x Age	15	2829.848	1.893	0.0231	0.282	0.1145
Speaker x Subjects(Age)	330	1494.973				
Sound x Speaker	75	487.166	2.379	< 0.0001	0.180	0.0042
Sound x Speaker x Age	75	362.419	1.770	0.0001	0.180	0.0446
Sound x Speaker x Subjects(Age)	1650	204.750				
Total	2303					

by-Age { $F(75,1650)=1.770$, $p=0.0446$} were found to be significant at the ***$p<0.05$*** alpha level. No other main effects or interactions were found to be significant at the specified alpha level

3.3.3 Sound-by-Speaker-by-Age Interaction

Since this ANOVA revealed a 3-way interaction, analysis and interpretation of the significant results were again focused on this highest order interaction, as discussed previously.

The simple-interactions comprising this 3-way interaction were analyzed to help isolate the causes of the interaction. The selection of the simple-interactions to analyze, however, was simplified by the absence of significant Sound-by-Age and Speaker-by-Age interactions from the overall analysis. Therefore, attention was focused on the Sound-by-Speaker simple-interaction for further analysis. Furthermore, since the 3-way Speaker-by Sound-by-Age interaction was present, while significant two-way interactions with the Age effect and a significant main effect for Age were not present, an obvious strategy was to analyze the Sound-by-Speaker interaction separately for each age group. That is, a 2-way ANOVA on Sound and Speaker was performed for each level of age. This strategy successfully isolated the probable cause of the significant 3-way interaction

3.3.4 Speaker-by-Sound Simple-Interaction

The results of these 2-way ANOVA procedures indicated a significant Sound-by-Speaker interaction for the younger subjects {$F(75,1650)=2.8585, p=0.0005$}, but no significant interaction for the older subjects { $F(75,1650)=1.2908$, $p=.2122$}. Since the Speaker-by-Age interaction from the overall analysis and the Speaker-by-Sound interaction for the analysis of the older age group were not significant, it is reasonable to conclude that the significant Speaker-by-Sound interaction for the ***younger*** age group was the probable cause of the Sound-by-Speaker-by-Age interaction.

3.3.5 Speaker-by-Sound Simple-Interaction (Younger Age Group)

Based on the 2-way ANOVA results, the Sound-by-Speaker interaction for the younger age group was identified as the probable cause for the 3-way interaction and was subjected to further analysis. At this point, the general strategy for analyzing this interaction followed that which was used for previous 2-way interaction analyses. Simple-effects F-tests for Sound were performed at each level of Speaker for the ***younger*** age group to determine simple-effects. Newman-Keuls post-hoc tests were then conducted on each significant simple-effect to determine differences between the levels of sound.

The results of the simple-effects F-tests for Sound at each level of Speaker appear in TABLE 3-12. The results indicated a simple-effect for Sound at speaker levels 1,2,7,8,12, 13 and 16. Figure 3-5 illustrates the Speaker-by-Sound simple-interaction for the younger age group along with the results of the Newman-Keuls analysis. Similar performing subsets of sounds are circled, and notable performance of sounds are highlighted with text and arrows, as in previous analyses. The Newman-Keuls analysis showed that the repeating pattern and buzzer were generally poorer performers. Exceptions to this trend occur at speaker levels 8 and 16, where the voice warnings performed worst as a group and the repeating pattern performed best, respectively. Once again, since a significant Sound-by-Speaker interaction was not present for the older age group, as well as interactions with Age from the overall analysis, these simple-effects appear to have resulted in the significant 3-way interaction.

3.3.6 Sound and Speaker Main Effects

Keeping in mind the results of the 3-way interaction analysis, analyses of the Sound and Speaker main effects were performed to help construct overall conclusions for the accuracy dependent measure. A Newman-Keuls test was performed on the Sound and Speaker main effects to determine significant differences between the levels of each main effect. A graphical representation of these results can be found in Figure 3-6 and Figure 3-7 for Sound and Speaker, respectively.

TABLE 3-12

Speaker-by-Sound (Young) Simple-Effects for Sound at each Speaker Level for Accuracy

Speaker	MS	***F***	***P***	***G-G e***	***G-Gp***
1	1532.609	7.48527	< 0.0001	0.180	0.0066
2	1944.393	9.49642	< 0.0001	0.180	0.0023
3	458.968	2.2416	0.0479	0.180	0.1354
4	183.426	0.89586	0.4830		
5	142.687	0.69688	0.6265		
6	198.061	0.96733	0.4367		
7	1845.444	9.01316	< 0.0001	0.180	0.0029
8	1056.584	5.16036	0.0001	0.180	0.0238
9	169.623	0.82844	0.5293		
10	354.816	1.73292	0.1239		
11	236.876	1.1569	0.3283		
12	799.023	3.90243	0.0016	0.180	0.0492
13	434.677	2.12296	0.0601		
14	75.202	0.36729	0.8712		
15	347.598	1.69767	0.1320		
16	912.619	4.45724	0.0005	0.180	0.0356

Note: All *p*-values were calculated using $df_{num}=5$ and $df_{den}=1650$.

All F-ratios were calculated using the MSE=204.750.

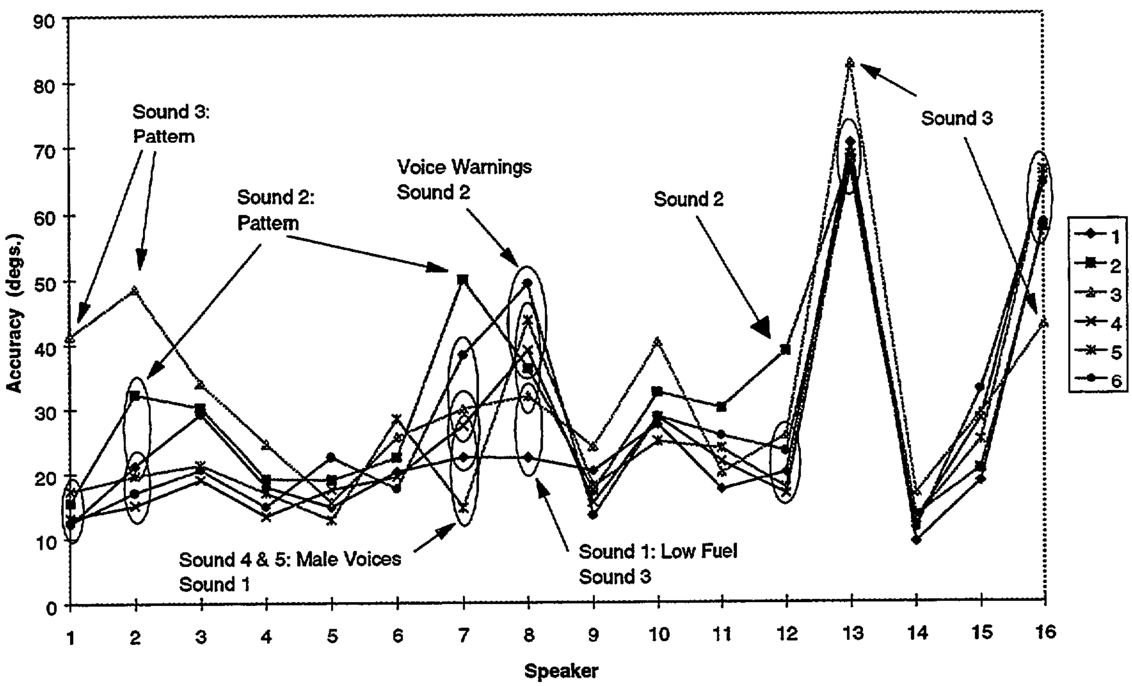


Figure 3-5. Sound-by-Speaker Simple-Interaction for Younger Age Group for Accuracy. Newman-Keuls results labeled for significant simple-effects of Sound.

As expected, the Sound main effect analysis showed a significant difference between Sound 2 and Sound 3 and the remaining four sounds. These two sounds were less accurately localized, although by only about 5 degrees from the best performing Sound 1. The voice warnings, on the other hand, performed well as a group and did not perform significantly different than Sound 1 (ie., Low-fuel warning).

Since the 3-way interaction highlighted the fact that the younger age group's performance with Sounds 2 and 3 was a strong source of the interaction, an analysis of the Sound main effect was conducted for the age groups separately. The results of these analysis are illustrated in Figure 3-8. Although the Sound-by-Age interaction was not significant, Figure 3-8 shows that the Sound main effect is caused primarily by the younger age group's performance. It appears that the older age group's accuracy scores are about equal for all sounds, although not significantly different than the younger age group, hence, the non-significant Sound-by-Age interaction. This finding supports the reasons explaining the significant Sound-by-Speaker-by-Age interaction

The Speaker main effect analysis showed that the Speaker 13 and 16 combination speaker levels performed significantly worse than the rest of the speaker levels. The remaining levels performed similarly. The Newman-Keuls analysis generated three groupings of non-significantly differing speaker levels for the remaining speakers. As an indication of the close performance among speakers, the best performing speaker level (Speaker 14) did not significantly differ from the next 11 best performing speaker levels. The intermediate performance level was attained by Speakers 7 and 12. This highlights the fact that even though the accuracy range between these 12 speaker levels was approximately 15 degrees, standard deviations were high for many of the scores. The standard deviations calculated for each speaker condition are illustrated in Figure 3-7 along the dotted line.

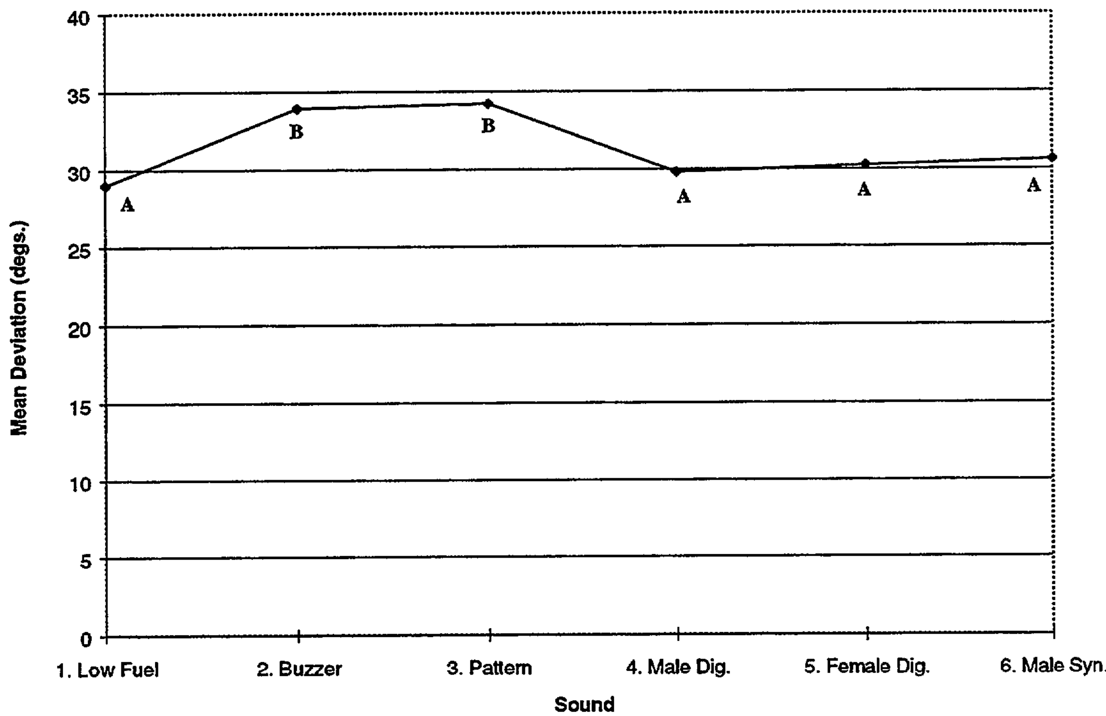


Figure 3-6. Sound Main Effect for Accuracy. Sounds labeled with the same letter were not found to be significantly different from one another at the p<0.05 level of significance.

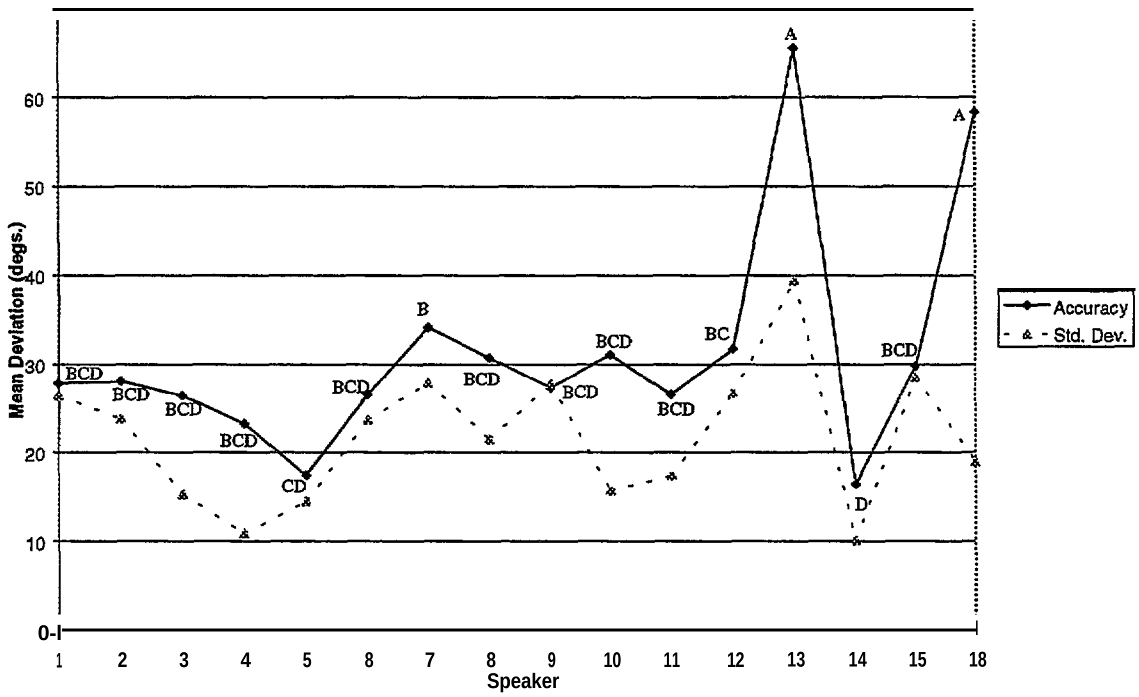


Figure 3-7. Speaker Main Effect for Accuracy (Speakers labeled with the same letter were not found to be significantly different from one another at the p<0.05 level of significance; dotted line represents standard deviation for each speaker's accuracy).

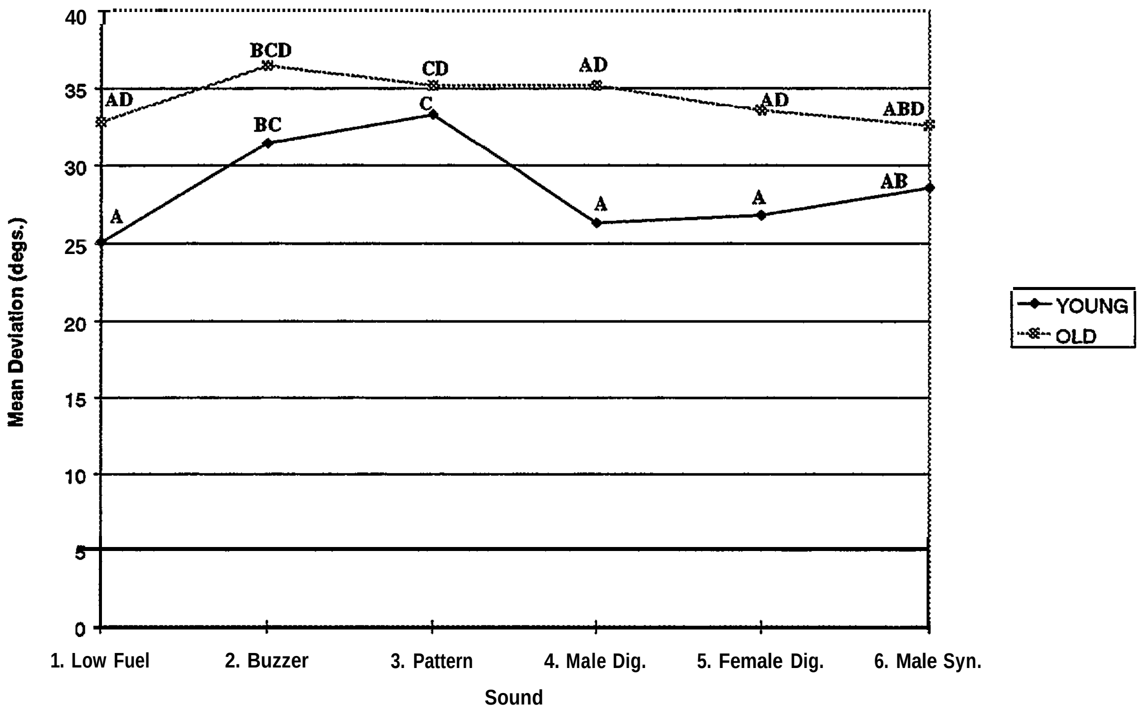


Figure 3-8. Sound Main Effect for Accuracy analyzed by Age Group (Sounds labeled with the same letter were not found to be significantly different from one another at the p<0.05 level of significance).

3.3.7 Descriptive Statistics

Descriptive data on response accuracy is shown separately for each of the six sounds, in Figures 3-9 through 3-14. In these figures, a separate bar chart is shown for each of the 16 speaker locations. The bar charts show the proportion of all responses that fall within various ranges of accuracy. The data are grouped into 15° accuracy bins for responses that were within 45° of the correct direction, and into broader 45° bins for responses with greater error than 45°. These figures complement that findings discussed in the preceding analyses, which examined mean errors. In contrast, these descriptive data provide more detail on typical levels of accuracy. They also show the frequency of substantially large errors, which could be an important consideration for practical warning systems. Errors exceeding 90° are a particular concern, since they may be considered perceptual "reversals" that could orient the driver away from the hazard.

The charts suggest that while the majority of responses were not highly accurate (within 15°), most responses were at least generally accurate (within 45°), with the obvious exceptions of Speakers 13 and 16. Although for most sounds and speaker locations there were relatively few perceptual reversals, these none-the-less did occur at a sufficient frequency for some speakers to warrant concern

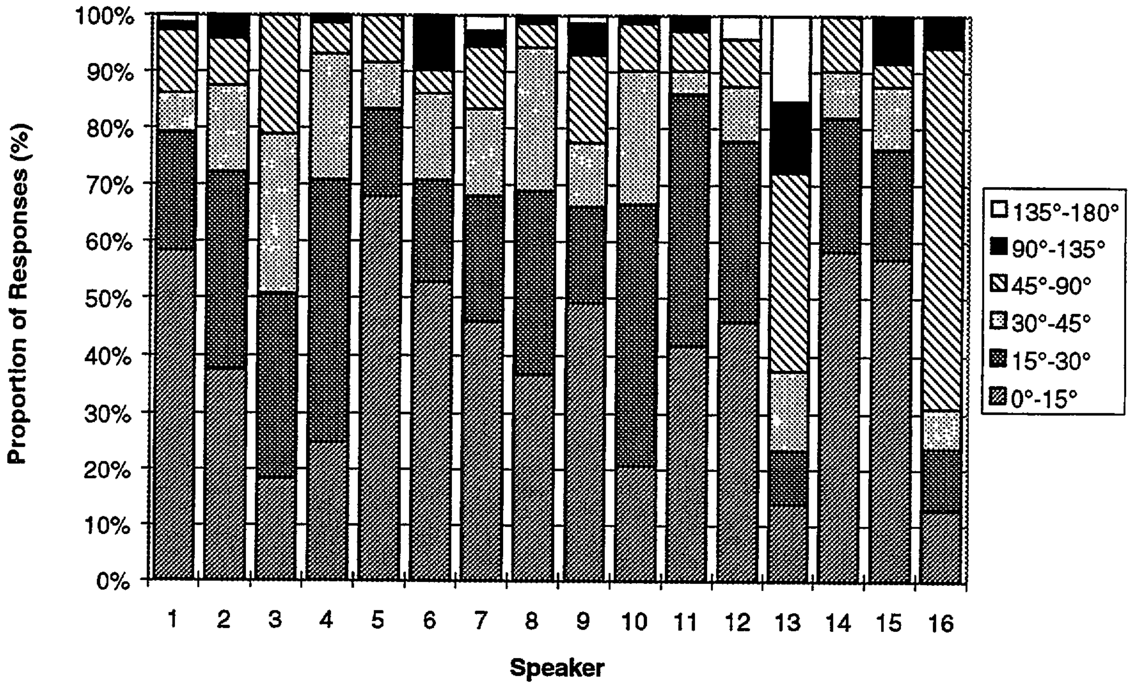


Figure 3-9. Proportion of Responses within each of Six Accuracy Bins for each Speaker for Sound 1 (Note: Bin sizes are 15° for first 3 bins and 45° for remainder).

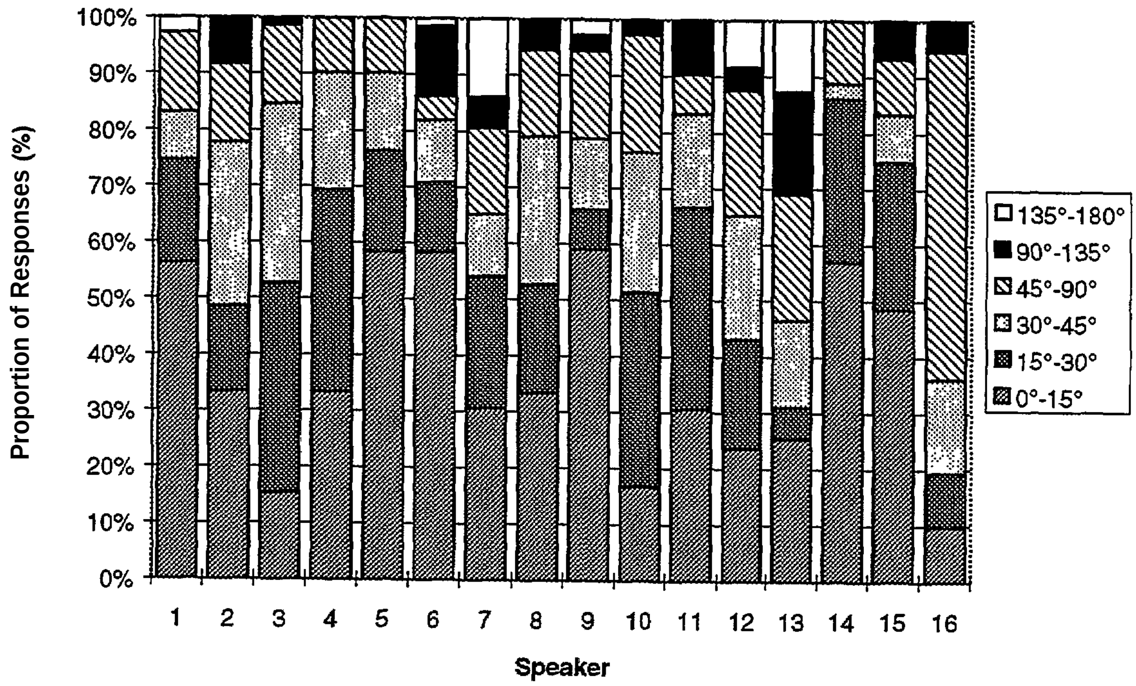


Figure 3-10. Proportion of Responses within each of Six Accuracy Bins for each Speaker for Sound 2 (Note: Bin sizes are 15° for first 3 bins and 45° for remainder).

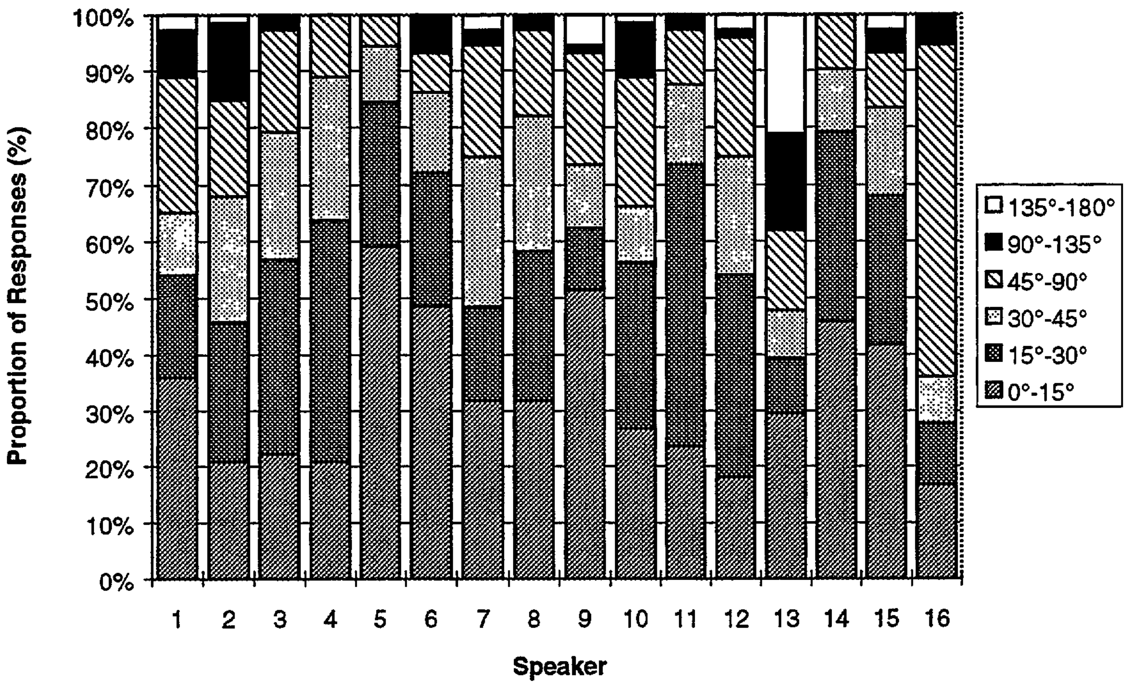


Figure 3-11. Proportion of Responses within each of Six Accuracy Bins for each Speaker for Sound 3 (Note: Bin sizes are 15° for first 3 bins and 45° for remainder).

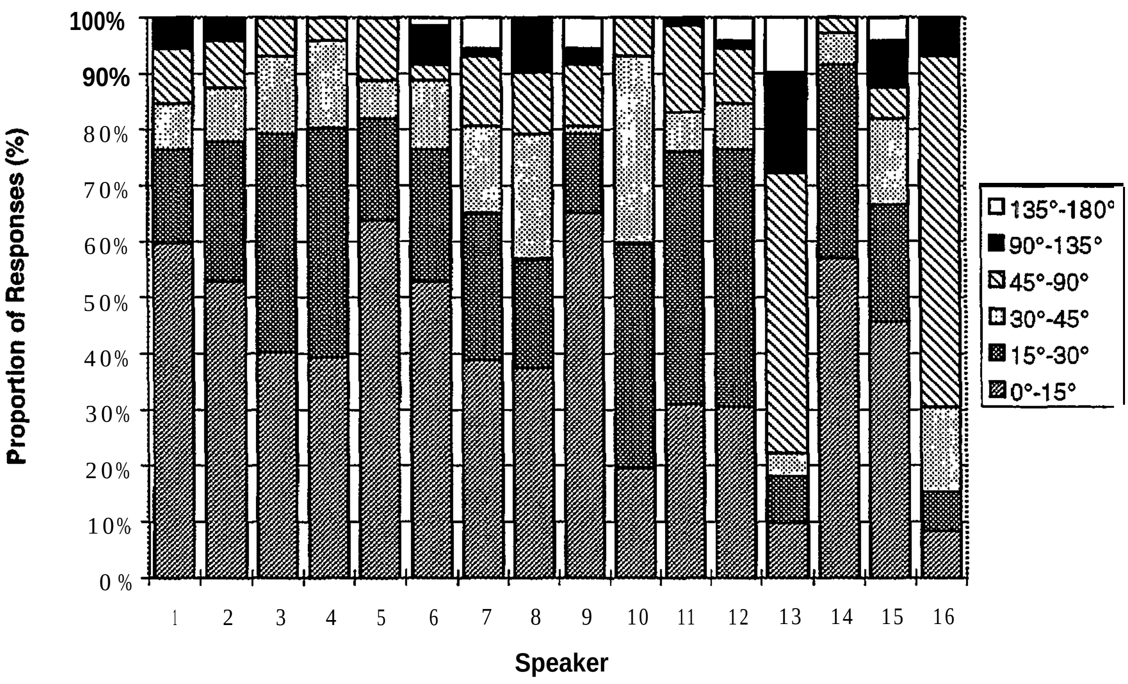


Figure 3-12. Proportion of Responses within each of Six Accuracy Bins for each Speaker for Sound 4 (Note: Bin sizes are 15 ° for first 3 bins and 4.5° for remainder).

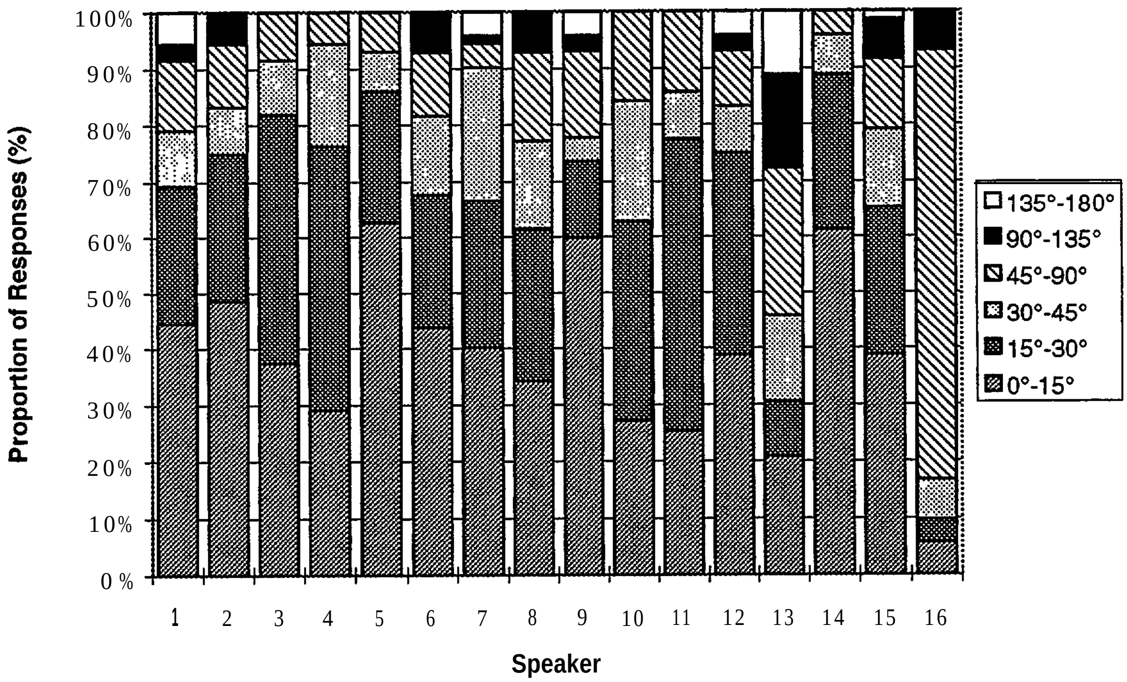


Figure 3- 13 Proportion of Responses within each of Six Accuracy Bins for each Speaker for Sound 5 (Note: Bin sizes are 15° for first 3 bins and 45° for remainder).

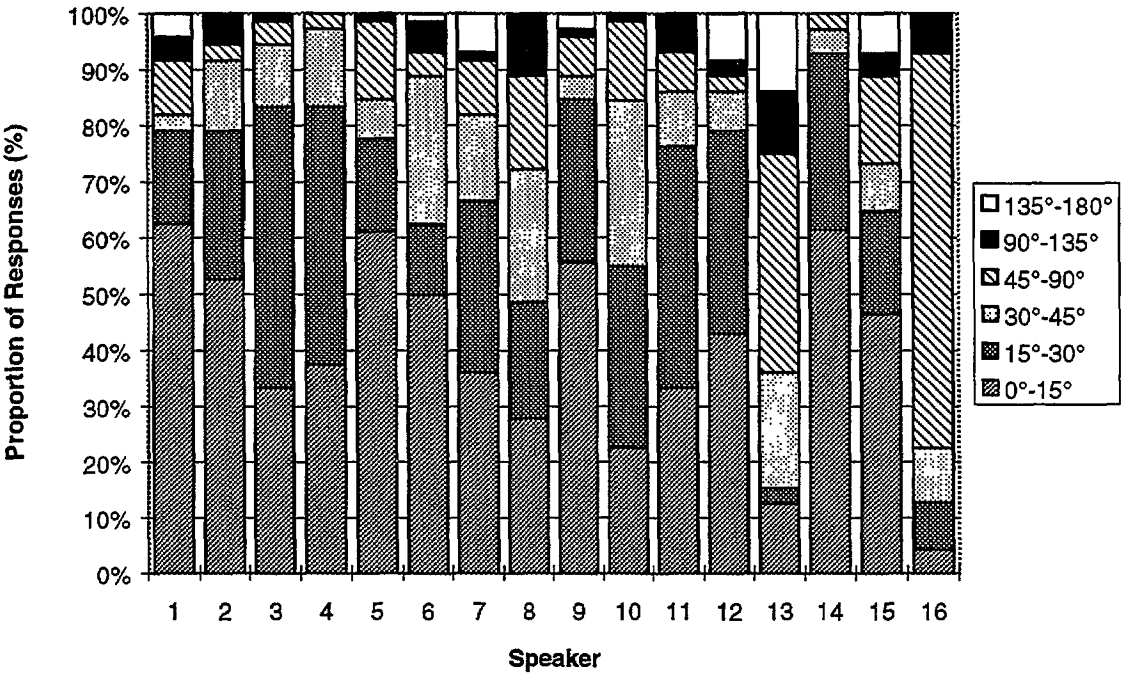


Figure 3-14. Proportion of Responses within each of Six Accuracy Bins for each Speaker for Sound 6 (Note: Bin sizes are 15° for first 3 bins and 45° for remainder).

3.4 ***AZIMUTH***

3.4.1 Data Reduction

The x- and y-coordinates of all joystick positions recorded during the experiment were transformed to an azimuth direction where a 0^o azimuth corresponded to a direction of the joystick that was anchored at directly in front of the subject's head and 90^o azimuth corresponded to a direction directly to the right of the subject. Transformation of the x- and y-coordinates to an azimuth direction involved mapping the passenger compartment relative to the 12 anchor points collected during joystick calibration and then to determine where each response fell within the coordinate space (Refer to ***Accuracy: Data Reduction*** discussion). The location of each response in the coordinate space (0^o360^o) was then used as the dependent measure for the ANOVA for azimuth. The purpose of this analysis was to determine how well the respective speaker locations provided a cue to the ***intended*** speaker azimuth direction.

An additional transformation of the data was required to account for speaker responses that were clustered near 0^o This was necessary to avoid responses such as 2^o and 355^o to be calculated in the ANOVA as differing by 353^o instead of only 7^o, assuming the correct direction was between 2^o and 355^o To avoid this problem, all 6912 responses were plotted by speaker and azimuth, and speaker responses that were affected were identitied. These responses were then assigned a value of 361^0 and higher to create a continuous interval scale for each speaker. A similar transformation was required for the Newman-K&Is post-hoc tests, which involved creating an additional mean representing responses above 361". Although the critical differences could be applied to the existing 16 means, the additional mean facilitated analysis and representation.

Descriptions of the twelve anchor points appear in TABLE 2- 10 and azimuth directions corresponding to the stimulus speakers appear in the TABLE 2-5 for reference.

3.42 Overall Analysis

TABLE 3-13 contains the ANOVA summary table for the azimuth dependent measure. Using the Greenhouse-Geisser correction where appropriate, the main effect of Speaker {$F(15,330)=459.944$, $p<0.0001$}, and the interaction of Sound-by-Speaker {$F(75,1650)=4.697$, $p<0.0001$} were found to be significant at the $p<0.05$ alpha level. No other main effects or interactions were found to be significant at the specified alpha level.

3.4.3 Sound-by-Speaker Interaction

Since the ANOVA revealed a 2-way interaction, analysis and interpretation of the significant results were again first focused on this interaction. A simple-effects F-test was conducted on the Sound-by-Speaker interaction for azimuth. An analysis of the simple-effects of Sound at each level of Speaker was performed. The ANOVA summary tables for these simple-effects F-tests appear in TABLE 3-14. The results of the tests indicated that the simple-effects of Sound were significant at 12 of the 16 speaker levels. A Newman-Keuls test was conducted on each of the significant simple-effects for Sound to determine significant differences between the levels of Sound at each speaker level. The results of the Newman-Keuls tests are incorporated in Figure 3-15 (Note: The Newman-Keuls test failed to find significant differences between sounds for Speakers 3 and 11 at the $p<0.05$ significance Level, although a significant simple-effect was detected).

Since the ordering of the means is dependent on the correct azimuth for the speaker, the Newman-Keuls ordering of sounds and lettering convention denoting significant differences appears directly on Figure 3-15 for each speaker where a significant simple-effect for sound was found. The correct azimuth for each speaker is depicted in Figure 3-l6; horizontal lines in this figure mark the respective baseline azimuth for each speaker (each horizontal line is Labeled with the respective speaker's number). In some cases, a dotted line may have two speakers associated with it (e.g., Speakers 6 and 15). These two figures facilitate recognizing the sounds within each speaker condition that performed closest to the correct azimuth. In general, although there was a simple-effect for Sound at 12 of the 16 speaker locations, the

TABLE 3-13

ANOVA Summary Table for Azimuth

Source	*df*	MS	*F*	*p*	*G-G e*	*G-Gp*
<u>Between-Subjects</u>						
Age	1	28390.702	3.272	0.0841		
Subjects(Age)	22	8675.551				
<u>Within-Subjects</u>						
Sound	5	537.282	1.333	0.2557		
Sound x Age	5	666.855	1.654	0.1518		
Sound x Subjects(Age)	110	403.130				
Speaker	15	1279504.821	459.944	< 0.0001	0.221	< 0.0001
Speaker x Age	15	4914.957	1.767	0.0381	0.221	0.1401
Speaker x Subjects(Age)	330	2781.869				
Sound x Speaker	75	1681.981	4.697	< 0.0001	0.153	< 0.0001
Sound x Speaker x Age	75	509.238	1.422	0.0114	0.153	0.1598
Sound x Speaker x	1650	358.111				
Total	2303					

TABLE 3-14

Simple-Effects for Sound at Each Speaker Level for Azimuth

Speaker	MS	***F***	***p***	***G-G e***	***G-Gp***
1	1225.461	3.42201	< 0.0001	0.153	0.0001
2	1809.496	5.05289	< 0.0001	0.153	< 0.0001
3	1042.669	2.91158	< 0.0001	0.153	0.0009
4	473.894	1.32332	0.0358	0.153	0.2052
5	423.026	1.18127	0.1415		
6	286.353	0.79962	0.8931		
7	5926.070	16.5481	< 0.0001	0.153	< 0.0001
8	936.282	2.6145	< 0.0001	0.153	0.0026
9	931.843	2.60211	< 0.0001	0.153	0.0028
10	481.037	1.34326	0.0288	0.153	0.1944
11	1021.081	2.8513	< 0.0001	0.153	0.0011
12	2109.758	5.89135	< 0.0001	0.153	< 0.0001
13	1901.879	5.3 1086	< 0.0001	0.153	< 0.0001
14	1212.903	3.38695	< 0.0001	0.153	0.0001
15	1137.010	3.17502	< 0.0001	0.153	0.0003
16	4848.234	13.5384	< 0.0001	0.153	< 0.0001

Note: ***All p-values*** were calculated using $df_{num}=5$ and $df_{den}=1650$.

All F-ratios were calculated using the MSE=358.111.

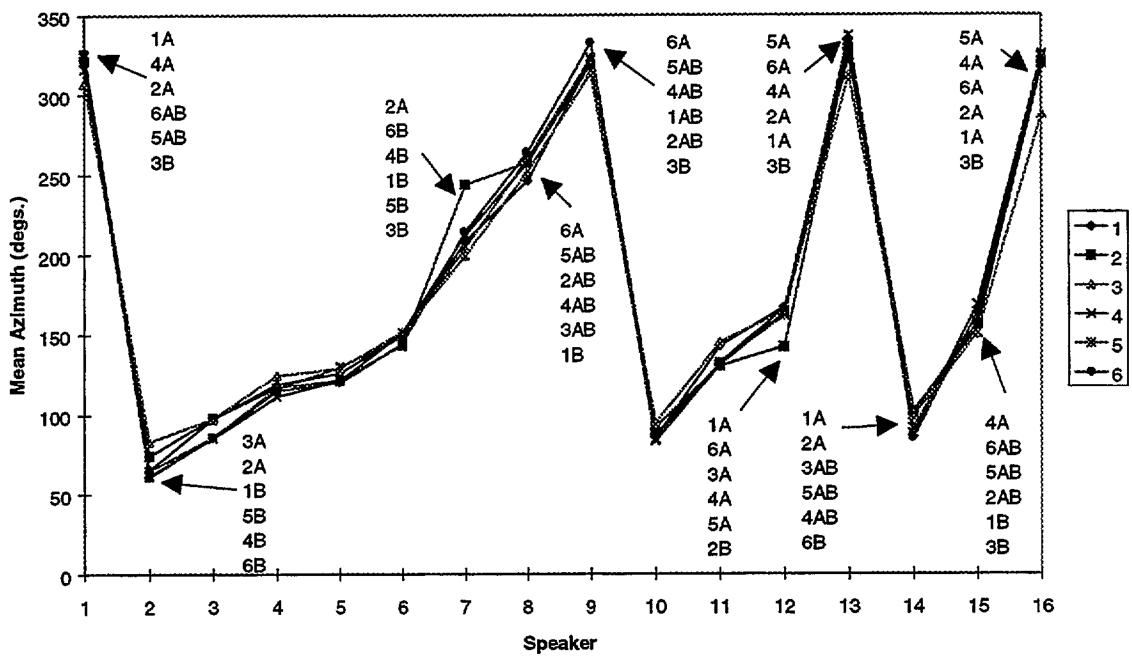


Figure 3-15. Mean Responses for each Sound and Speaker for Azimuth. Newman-Keuls ordering of sounds and lettering convention denoting significant differences appear for each speaker where a significant simple-effect for sound was found (p<0.05).

Newman-Keuls groupings indicate that many of these simple-effects were due to differences between the lowest and highest ranking sounds in the mean orderings. Furthermore, a maximum of three groupings (i.e., A, AB, B) was generated, and in 2 of the 12 cases no significant differences were found. In addition, Figure 3- 16 provides a visual representation of the relative difference between perceived and actual azimuths and clearly shows that responses were rarely normally distributed around the correct azimuth, which indicates a difference between the actual and perceived azimuth locations.

3.4.4 Special Analysis for the Azimuth Dependent Measure

It should be noted that the overall proximity to the correct azimuth is as important as the Newman-Keuls ordering of the sounds for significant simple effects, and of primary importance for non-significant simple effects. Therefore, each speaker should first be gauged on its ability to present sounds that can be localized as originating from its physical azimuth location. Then, the ordering of sounds becomes important to determine which sounds are best localized as originating from the respective speaker azimuth.

In addition to the above analyses, the interacting main effect of Speaker was subjected to post-hoc tests to determine the speaker locations that resulted in the same ($p<0.05$) perceptual localization of sounds. The results attained from the Sound-by-Speaker analyses above are then applied to the groupings generated by this test to help determine the speakers within the group that are best suited for indicating a particular hazard direction.

3.4.5 Speaker Main Effect

The Newman-Keuls test was performed on the Speaker main effect from the overall analysis. The results of the test appear in TABLE 3-15. The procedure partitioned the 16 speaker levels into 8 groups on the basis of having elicited similar perceptual azimuth locations. These groups are presented in blocks of statistically similar speaker locations in the column titled ***Speaker Placement.***

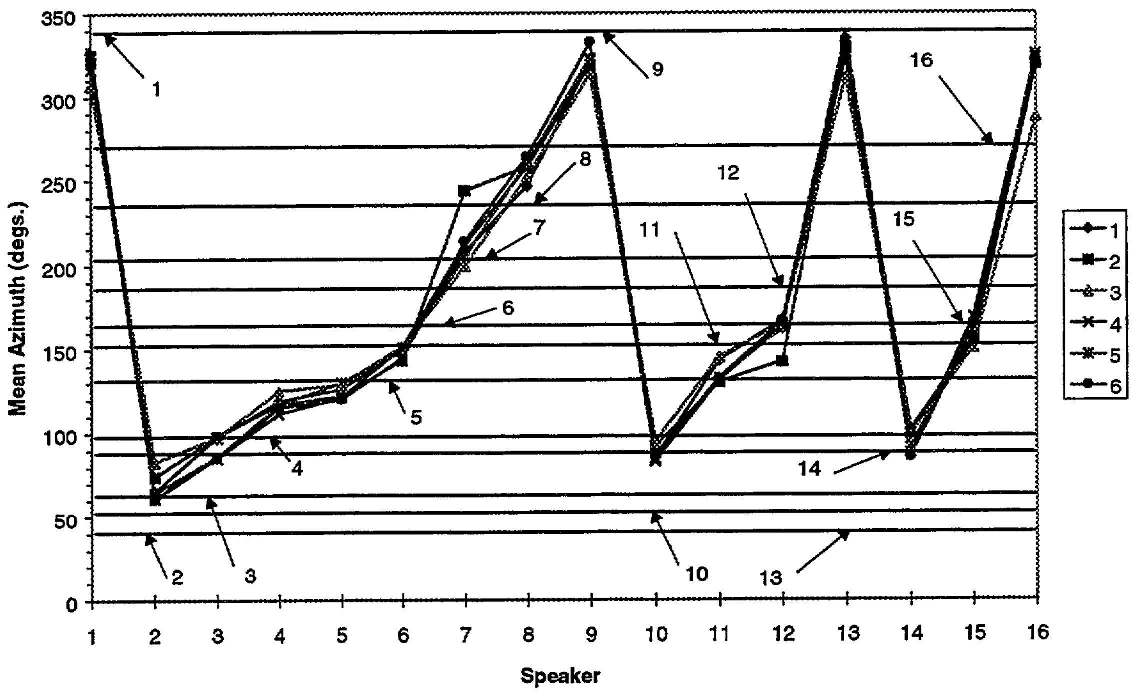


Figure 3-16. Correct Azimuth for Each Speaker Relative to Mean Responses for Azimuth. Horizontal lines mark the respective baseline azimuth for each speaker (each dotted line is labeled with the respective speaker's number).

TABLE 3-15

Newman-Keuls Test on the Speaker Main Effect for Azimuth

Speaker Placement	Actual Azimuth (deg.)	Mean Response (deg.)	Difference	Spk	Location	Newman-Keuls Groupings
Front Center (Virtual)	401.1	428.1	27.0	2	Front	H
A-pillars	41.1	***327.2***	-73.9	13	Front	A
Middle Left A-pillar	338.5	***321.8***	-16.7	9	Front-L	A
Left A-pillar	339.4	319.4	-20.0	1	Front-L	A
Left A- & C-pillars	270	315.7	45.7	16	Left	A
Left B-pillar	236.7	256.0	19.3	8	Left	B
Left C-pillar	203.4	***213.5***	10.1	7	Rear-R	C
Left Deck	185.8	160.8	-25.0	12	Rear-L	D
C-pillars	166.8	159.2	-7.6	15	Rear	D
Rear Center	166.8	148.1	-18.7	6	Rear	D
Right Deck	152.1	135.5	-16.6	11	Rear-R	E
Right C-pillar	132.4	124.6	-7.8	5	Rear-R	EF
Right B-pillar	101.1	117.1	16.0	4	Right	F
Right A- & C-	90	94.4	4.4	14	Right	G
Right A-pillar	***65.5***	91.5	26.0	3	Front-R	G
Middle Right A-	***57.3***	87.7	30.4	10	Front-R	G
Front Center	***41.1***	68.1	27.0	2	Front	H

Note: Newman-Keuls calculations based on MSE=2781.869 and ***df=330.***

Speakers with the same letter are not significantly different ($p<0.05$)

Placements within the same box are not significantly different.

The direction and number of degrees off that the mean azimuth response (in column Mean) of the speaker was from the actual azimuth location is also specified in TABLE 3-15 in the column titled ***Difference.*** Negative values indicate that the mean response was to the left of the speaker while a positive response indicated an azimuth to the right of the speaker, when facing the speaker.

The front center speaker was not grouped with other speakers. It was localized approximately 27° to the right of its actual position. The physical location of this speaker was unique in the sense that its position, centered above and in front of the rear view mirror, was close to the driver and at an angle where the speaker's axis may have projected backward to a virtual speaker location several degrees to the right of the speaker. This may have contributed to the surprisingly poor localization performance of the speaker location.

The first group of speaker conditions consisted of the A-pillars, middle-left A-pillar, left A-pillar and left A- and C- pillars. The performance of the combination speakers in this group indicate that the member of the speaker pair closest to the driver weighted the perceived location of the stimulus in that direction. As a result, the combination speakers did not perform as accurately relative to the expected virtual direction; about a 74° and 46° difference for the A-pillars and left A- and C-pillars, respectively. As a result, both speaker levels were perceived to originate near the left A-pillar position. As expected, each of the speakers mounted on the A-pillar were localized similarly, due to their close azimuths (within 1° of each other), but further to the left (~ 18°) than intended for both speakers. This position corresponded roughly with the driver's side-view mirror location.

The left B-pillar was the only member of the next Newman-Keuls grouping, followed by the left C-pillar, which was also a single member grouping. Both of these speakers were localized fairly well, 19° and 10°, respectively. However, both of these speakers were localized to the right of their actual azimuth locations, bringing their perceived locations to be closer to directly left and towards the left rear door, respectively.

The next grouping was comprised of the left deck C-pillars, and rear center speaker(s). The left deck speaker was localized approximately 25° to the left of its true position, or towards the center of the rear deck The combination speaker in this grouping did not appear to be biased toward any one speaker member of the pair, as previously discussed combination speakers had. It was accurately localized to its intended position (~8” to left), and its localization accuracy was among the best of all the speakers. The rear center speaker was localized approximately 19° to the left of the center position, making it less accurate than the C-pillars combination.

The right rear of the vehicle was the location of the next grouping of speakers, which included the right deck, and right C-pillar. The perceived location of the right deck speaker was about 17° to its left. The right C-pillar was also grouped with the right B-pillar from the next grouping. These last two speakers’ perceived locations fell between the speakers--although their physical locations were 31° apart, the difference between the perceived locations was only about 7”. This location corresponded roughly to the middle of the right rear door.

The right A- and C-pillars, right A-pillar, and middle right A-pillar formed the final group of speakers. The combination speaker condition in this group performed the best among all the speaker locations. Its mean perceived location was approximately 5” to the intended ***virtual*** direction. The speakers mounted on the right A-pillar, however, did not perform as well as the speakers on the left A-pillar. These speaker were localized approximately 25° to 30° to the right of the A-pillar, respectively, or more generally, directly to the right of the subject.

3.4.6 Azimuth Conclusions

The Newman-Keuls orderings presented in Figure 3-15 follow those generated for the accuracy dependent measure shown previously in Figure 3-5. This is not surprising since the azimuth dependent measure for the simple-effects of Sound at each Speaker is also used in similar form to generate the accuracy dependent measure. Therefore, the results for the azimuth dependent measure largely confirm the results found from the accuracy analysis. However, of importance in the azimuth analysis is the fact that Figure 3-15 and Figure 3-16 provide a direction of the perceived location relative to the actual azimuth location. This established a measure of the ability of each speaker location to provide a directional cue to its actual azimuth location, as opposed to strictly measuring the accuracy of localization. It also allowed for post-hoc grouping of the speakers that represented statistically insignificant perceived locations of sound (See TABLE 3-15). These groupings may be of utility for design applications.

Therefore, the most meaningful information gathered from the analysis of azimuth is from the Newman-Keuls ordering of the Speaker main effect, since the results of the Speaker-by-Sound analysis showed relatively insignificant effects between sounds at the perceived speaker locations compared to this ordering. The simple-effects of sound at each speaker location, however, are discussed where appropriate in the selection of speakers based on azimuth ***(See Discussion).***

3.5 4-FACTOR ANOVA RESULTS

As discussed in the Experimental Design section, a fourth variable, gender, was manipulated such that an equal number of male and female participants was achieved in each age group. Although, gender was not formally analyzed in this experiment, gender was added to the 3-factor ANOVA, post-hoc, resulting in a 4-way mixed factorial ANOVA design with gender and age nested within subjects. This 4-way ANOVA procedure was conducted on each of the four dependent measures and the results were found to be identical to the 3-way ANOVA procedures conducted--no significant main effect or significant interactions were identified for gender.

4.0 DISCUSSION

The findings of this experiment suggest that there is promise to the use of acoustically localized warning signals for alerting drivers in crash avoidance situations. Subjects were able to localize the warning with reasonable speed and accuracy under the conditions of this experiment. However, both the choice of the particular auditory signal, and the choice of the speaker location, had important effects, so that it would be misleading to suggest that CAS designers may use any warning signal or speaker site. It is also important to note that this experiment was limited in terms of the vehicle interior, noise conditions, driver variables, and driving task demands. It investigated a reasonable situation as a preliminary case, and found merit to the concept. This study did not attempt to determine the extent to which the effectiveness of localized warnings is generally maintained across the range of vehicles, drivers, and situations.

In the sections that follow, there will first be a general discussion of the speed and accuracy of responding. This will be followed by a brief discussion of the performance of various warning sounds and speaker locations. The limitations of this experiment, and the related needs for additional research, will be considered. Finally, based on these findings, some recommendations will be put forth regarding effective localized crash avoidance warnings.

4.1 SPEED OF RESPONDING

Two measures of the speed of responding were collected: response time (initial movement of the joystick) and decision time (button press to indicate when precise orientation of the joystick was achieved). While the two measures led to generally parallel tidings, the decision time measure probably is not very meaningful in absolute terms, since it is really a measure of people’s ability to finely orient a joystick The response time measure is more similar to a general orienting response to a signal, and will be the measure discussed here.

Across all sounds and speakers, younger subjects were able to respond with a mean time of less than one second (0.95 s). Older subjects required about a half second longer. Both the particular sound and the particular speaker influenced the response time, so that the better conditions were about 20% faster than the mean Thus it appears that initial orientation toward the signal can occur quite quickly. Reaction time measures also depend on the particular response required. 'It seems likely that if the experiment had been able to measure a naturally occurring orienting response (e.g., eye movement in the direction of the signal), the response time would be even briefer. The measured response times are slightly longer than typical findings for on-road brake reaction times to an arbitrary signal (e.g., a loud tone), and notably shorter than typical driver brake or steering response times to unexpected roadway events. Lerner, Ratte, Huey, McGee, and Hussain (1990) reviewed driver reaction time studies, and found that mean on-road response times to roadway events generally exceeded 1 s, and were typically around 1.2-1.3 s. Thus the response time data suggest that, particularly for the better choices of signal, orientation toward the warning source can occur rapidly enough to influence driver emergency maneuvers. However, given the slower response times of older subjects in this experiment, the potential benefits to older drivers may not be as great. The sound-by-age interaction observed in the experiment suggests that older drivers may be particularly influenced by the choice of warning signal. The two stimuli (sounds 2 and 3) for which they performed significantly worse were also those with narrower and higher frequency spectra suggesting that these findings are quite possibly due to the effects of presbycusis.

In summary, the speed of response is importantly influenced by the particular stimulus, but for appropriately chosen signals, it appears reasonably rapid and capable of alerting drivers quickly enough to influence their maneuvers.

4.2 ACCURACY OF RESPONDING

Subjects were generally able to localize the warning sounds with reasonable accuracy, although not with great precision; that is, the large majority of responses were in the approximate direction of the actual sound source, but usually were not directly at it. For the better conditions of warning sound and speaker location, the mean errors in localization were about 10-20°. Since some conditions produced very poor performance, the overall mean error was just over 30°Although the older subjects showed an overall mean younger subjects, the main effect of age was not statistically significant. The general conclusion, then, is that localization is accurate enough to orient the listener in the direction of the sound source, provided that appropriate sounds and speaker locations are chosen

Even though localization was generally accurate, there was some incidence of errors large enough to orient the listener in an inappropriate direction. Excluding the poorer performing sounds (2 and 3) and speaker locations (especially 13 and 16), subjects responded within the correct quadrant (i.e., within plus-or-minus 45°) on the vast majority of trials (approximately 80-95%). Yet some errors exceeded 90°, which indicates a perceptual reversal. Such reversals occurred on at least a few percent of cases for almost every sound/speaker condition. Therefore, even though mean or modal, performance, may be acceptable, CAS designers who attempt to use acoustically localized signals must be alert to the occurrence of perceptual reversals in perceived location. Some rate of occurrence is to be expected, although for the conditions of this study, it is probably acceptably low for some signals. However, this is a concern that will have to be carefully monitored in further evaluations that take into account a broader range of vehicle interiors, driver seating positions, vehicle occupancy, and noise conditions.

4.3 EFFECTS OF WARNING SOUND AND SPEAKER LOCATION

The particular warning sound had a statistically significant effect on both the response time and the response accuracy. This is noteworthy since all six sounds were initially selected as potentially reasonable candidates, based on existing recommendations for warning signals, and none had obviously poor characteristics for localization (e.g., narrow tonal spectrum, steady signal). Although significant, the main effect of sound type, across all speaker locations, was not particularly large, for either speed or accuracy of response. The range of mean response times for each sound was from about 1.12 s to 1.26 s. The range of mean localization errors was from about 29^{o} to 34^{o} For both speed and accuracy, the primary basis of the effect was the poorer performance of sounds 2 (buzzer) and 3 (repeating pattern). The three voice messages (sound 4,5,6) and the aircraft low fuel warning (sound 1) were all roughly comparable, although response time to sound 1 was significantly faster than to other sounds for the younger subjects.

Although the effects of sound, averaged across all speaker locations, were not particularly large, there was a significant sound-by-speaker interaction. The effect of the particular sound signal was quite pronounced for some speaker locations, for both speed and location accuracy measures. In particular, sounds 2 and 3 were particularly influenced by speaker location, although they performed comparably to other sounds at some locations, they were very much poorer for other locations. Overall, the conclusion is that among the six candidate alarms, sound had a modest though meaningful effect, and that once speaker location is taken into account, it may be seen to be quite important. Among the three acoustic warnings, sound 1 was superior in performance to sounds 2 and 3. The differences among the three voice warnings were not as pronounced.

The particular speaker location had a statistically significant main effect on both the speed and the accuracy of localization. As noted, it also interacted in important ways with the specific warning sound used. The magnitude of the speaker effect was greater than that of the warning sound, primarily because of substantially poor performance for some locations. Overall mean response times ranged from 1.01 s (speaker locations 1 and 9, front left A pillar) to 1.59 s (location 13, combining speaker locations 1 and 3). Overall mean localization error ranged from 17° (speaker location 14) to 65° (speaker location 13). Speaker locations 7,13, and 16 performed more poorly than other locations, in terms of both speed of response and accuracy of localization. The concept of combining two speaker locations as a means of perceptually generating a virtual location between them clearly did not work for locations 13 (using speakers on the right and left A pillars) and 16 (using speakers on the left A pillar and left C pillar). However, other speaker combinations (14 and 15) did work quite well; in fact, location 14 (combining speakers on the right A pillar and right C pillar) had the greatest mean accuracy of all the speaker locations.

Because of the sound-by-speaker location interaction, the effectiveness of various speaker locations must be considered for the particular sound. Sound 1 was generally effective across the range of speaker locations, with the exception of the paired-speaker conditions, while other sounds showed more variability. Some implications of the differences among speaker locations are discussed further in Section 4.5.

4.4 LIMITATIONS AND ADDITIONAL RESEARCH NEEDS

As an initial investigation into the possibility of using acoustically localized warning signals in the vehicle, this experiment was designed around a single prototypical situation All sounds were presented in the same passenger vehicle (1995 Ford Taurus sedan), with no passengers present. A single, rather substantial background road noise was present, but the vehicle radio was not on. Seat position was adjusted so that all subjects had similar head locations within the sound field, and the secondary task was used to promote the likelihood that the subject was facing forward. While a range of hearing ability was tolerated, none of the subjects suffered severe or asymmetric hearing loss. Under these reasonable conditions of study, acoustically localized warning signals appeared promising. However, the generalizability of these findings is not known. It will obviously be important to extend the evaluation to additional environments. These would include:

* Vehicle interior: layout, materials and fabrics, seat/headrest configuration
* Noise conditions: road/traffic noise, stereo system, conversation, open windows
* Occupancy conditions: other passengers or objects in the sound field
* Driver-selected head locations within the three-dimensional field
* Driver hearing abilities

Since perceptual localization is a complex phenomenon sensitive to many details of the acoustic environment, the robustness of the present findings is not known. Further research will have to take into account a broader range of vehicle interiors, driver seating positions, vehicle occupancy, and noise conditions. Signal reproduction capabilities should also be considered, since the nominally same warning signal, reproduced via different transducer systems, might result in different abilities to localize. This study used a full-range 3.5” automotive speaker, which reproduced the frequency components of the sounds fairly well. Manufacturers may face constraints that require other devices, so that adequate performance with additional speakers, buzzers, and other transducers should be confirmed.

Another limitation of the present research is in the set of stimuli evaluated. Although the six sounds and 16 speakers resulted in a rather large set of 96 conditions, this is still only a small subset of the numerous possibilities. The three acoustic and three voice warnings were all reasonable candidates based on previous research (Tan and Lerner, 1995) and recommended signal characteristics. Nonetheless, there was meaningful variability among them and many additional signals potentially could be considered. While the number of reasonable speaker locations within the vehicle is somewhat constrained, there may also be additional candidates beyond what was evaluated here, and for radically different vehicle types (e.g., vans, utility vehicles, pickup truck cabs), an entirely different set of possibilities emerges.

The primary dependent measures of this experiment were the speed and accuracy of localization, as measured through joystick manipulation. While this procedure was effective, other more direct measures of orientation, such as eye movement, may prove useful and might provide more meaningful measures of response time. The present experiment did not attempt to measure the time required to recognize and react to an external hazard event. However, since this is the ultimate purpose of the warning, some direct measures of driver performance ultimately should be included. Perceptual localization of the signal is the appropriate measure for initial evaluation, comparison of alternatives, and refinement of the stimulus conditions. Driver performance measures of hazard recognition or vehicle control response time, particularly for drivers not expecting a warning signal, are appropriate for subsequent evaluation of the potential safety benefits of acoustically localized signals.

4.5 RECOMMENDATIONS FOR USE

Some recommendations can be made for acoustically localized in-vehicle warnings, based on the present findings. However, it is important to note these caveats:

(a) Because of the preliminary nature of the study, and the limitations and concerns discussed in the preceding section, it is not possible to recommend acoustic localization as an in-vehicle warning technique at this point. The experimental findings are encouraging, but many questions remain

(b) The findings described here deal only with acoustic localization. This is certainly not the sole criterion for a good crash avoidance warning. Therefore this or any other localization study should not be taken to define the best possible warning, but only one aspect of it. However, all six of the sounds investigated here did appear as reasonable candidates based on other criteria as well (Tan and Lerner, 1995).

(c) Some of the findings (particularly regarding speaker locations) could be idiosyncratic to the vehicle tested.

Regarding the choice of sound, the aircraft low fuel warning (sound 1) was clearly more effective than the other acoustic signals tested (sounds 2 and 3), in both speed and accuracy. It also performed well on other criteria in the Tan and Lerner (1995) study, and did not produce strong indication of annoyance in another study which investigated on-road annoyance by nuisance signals (Lerner, Dekker, Steinberg, and Huey, 1996). Therefore sound 1 is recommended over sounds 2 and 3, and in fact appears to be a good candidate for consideration if an acoustic CAS warning alarm is standardized.

Among the three voice warnings there was relatively little difference in performance. The male digitized voice may have marginally better performance in terms of fewer large errors (perceptual reversals). All three performed about as well as sound 1 in terms of speed and accuracy, except that sound 1 was responded to about 0.2 s faster than the voice signals for younger subjects only. Based on this difference in response time and on the indication of greater annoyance by inappropriate voice alarms in the Lerner et al. (1996) study, there may be some advantages to acoustic signals. However, this should not be taken to imply that acoustic signals should be used instead of voice warnings, and in fact, the voice warnings, as a group, performed better in this experiment than the acoustic warnings, as a group. There are many factors that CAS designers may wish to consider in choosing between acoustic or voice warnings for particular applications. Where a voice warning is used, signals similar to any of the three evaluated here would appear reasonable.

Considering speaker locations, it should first be noted that this experiment did not address the question of how finely a CAS should attempt to define location (i.e., how many sound source locations would be optimal). The desired degree of precision remains to be specified. Specific design decisions will depend on the number and location of speakers and the particular warning sound used; the detailed findings of this report can be used to support some decisions for a particular case. Some more general recommendations are considered below.

In general, the speakers that were not aimed directly at the driver head position (10, 11, 12) did not perform as well This was mainly attributable to interaction effects with warning sound type, so that the difference was not great for the better sounds. Nonetheless, it suggests that the strategy of aiming the speaker at the driver is more generally preferred. Similarly, although the good performance of speaker condition 14 suggests that the combination of pairs of speakers to create a virtual location might be feasible for at least some locations, the generally poor performance of these pairs, and their large interactions with sound type, even in the absence of other passengers in the acoustic field, suggests that the strategy of combining speakers is risky. The findings therefore suggest the use of individual speakers, aimed directly toward the driver head position. It especially should be emphasized that the simultaneous use of speakers on the left and right A pillars can lead to large errors and perceptual reversals.

For the general case of a hazard in front of the vehicle, the speaker locations on the left A pillar (1 and 9) led to response times about 0.2 s faster than for the location (2) centered above windshield. If the fineness of discrimination between these locations is not required, the A pillar locations appear preferable.

Warnings for hazards to the left side of the vehicle are important for blind spot warnings. Of the four speaker conditions oriented toward the left or left rear, none were ideal, although location 8 (B pillar) is probably preferred. Response times to location 7 (left C pillar) were relatively slow, and localization was poor for some sounds. Response times were also slow to location 12 (rear deck), and there were serious problems with localization for the combined A and C pillars (speaker condition 16). Speaker 8 was responded to more quickly than the other locations, and was localized well for sound 1 (low fuel warning), but was not localized well for the voice signals.

In general, all of the speaker locations toward the right side of the vehicle (3,4,5, and 14) performed well. Although the combination of two speakers (condition 14) performed well, the general concerns about this strategy suggest that speakers 4 or 5 be used for right-side hazards or blind spot warnings.

4.6 CONCLUSION

Under the conditions of this experiment, subjects were able to localize the direction of a warning signal with reasonable speed and accuracy. This indicates that directional acoustic cues have the potential to speed driver response to hazards. However, there was meaningful variation among alternative warning sounds and speaker locations. Auditory warnings should not be viewed as generally adequate for localized warnings without specific consideration of the signal and source. Some choices can lead to substantial error. The better-performing sound/speaker combinations of this study led to broadly correct, though imprecise, orientation (roughly 90% of responses within the correct quadrant of the field around the source), with relatively few perceptual reversals. Although performance appears promising for the prototypical listening situation used in this experiment, the robustness of the findings across a realistic range of vehicles and listening conditions still remains to be demonstrated.

5.0 REFERENCES

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APPENDIX A

TIME-SERIES PLOTS OF SEVEN WARNING SOUNDS

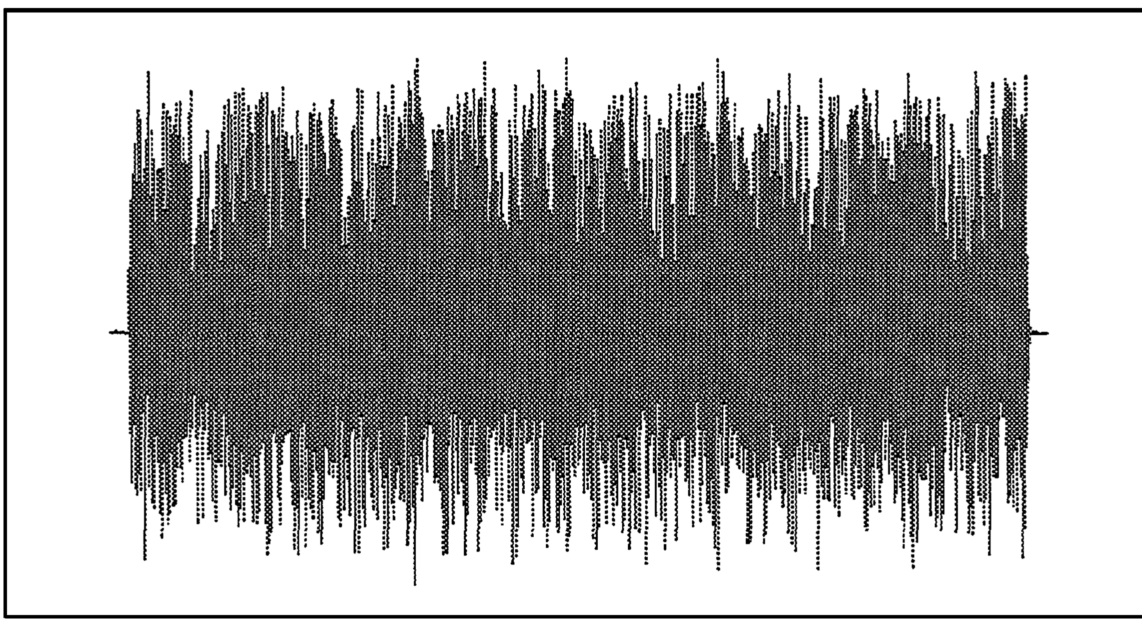

Figure A-l. Time-series plot for Sound 1: Low fuel warning.

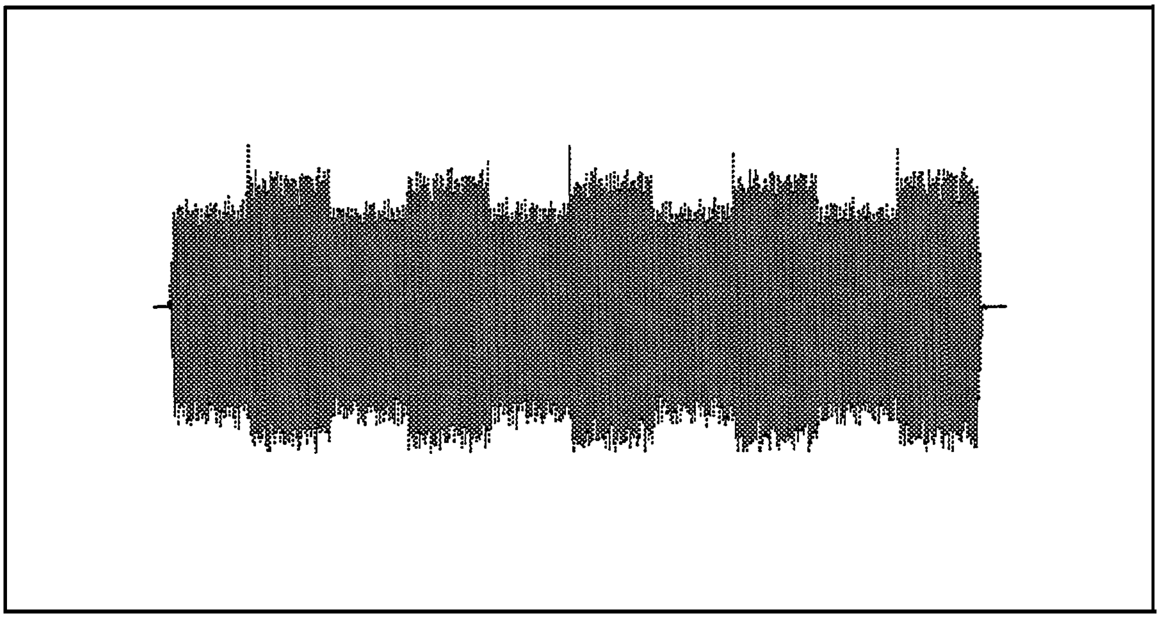

Figure A-2. Time-series plot for Sound 2: Radio Shack Buzzer.

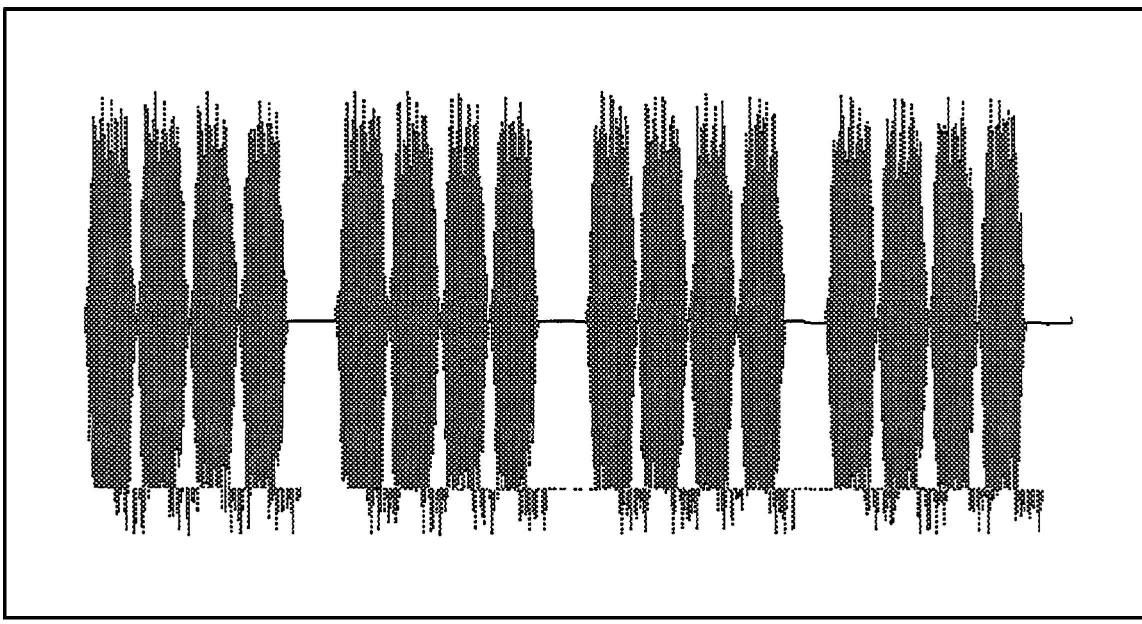

Figure A-3. Time-series plot for Sound 3: Repeating Pattern.

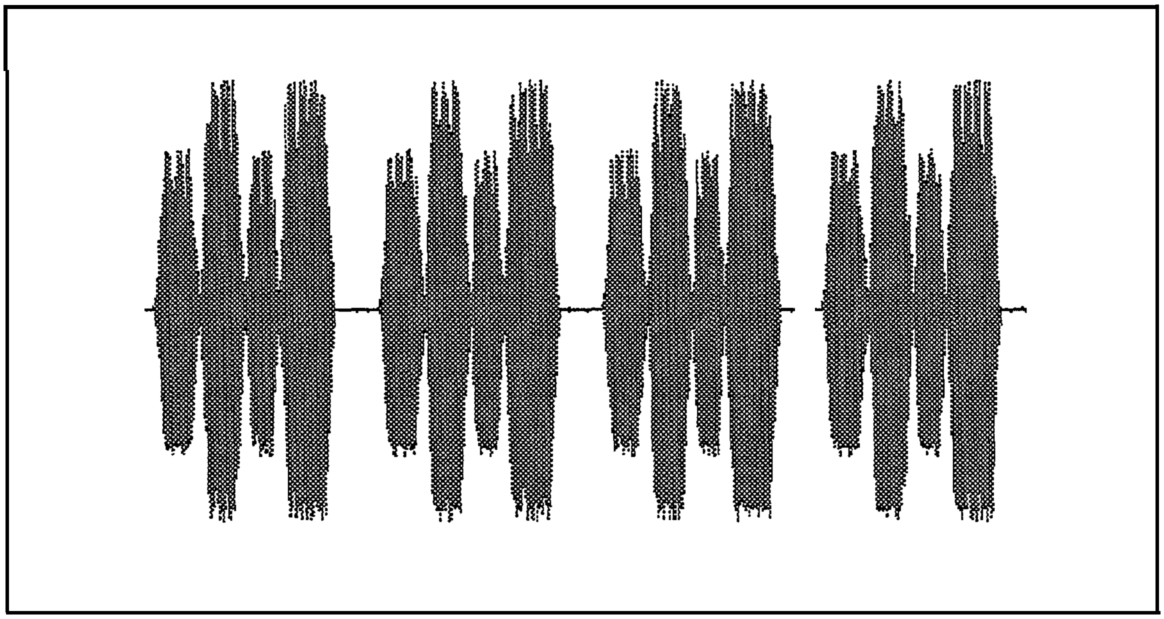

Figure A-4. Time-series plot for Practice Sound: Repeating pattern.

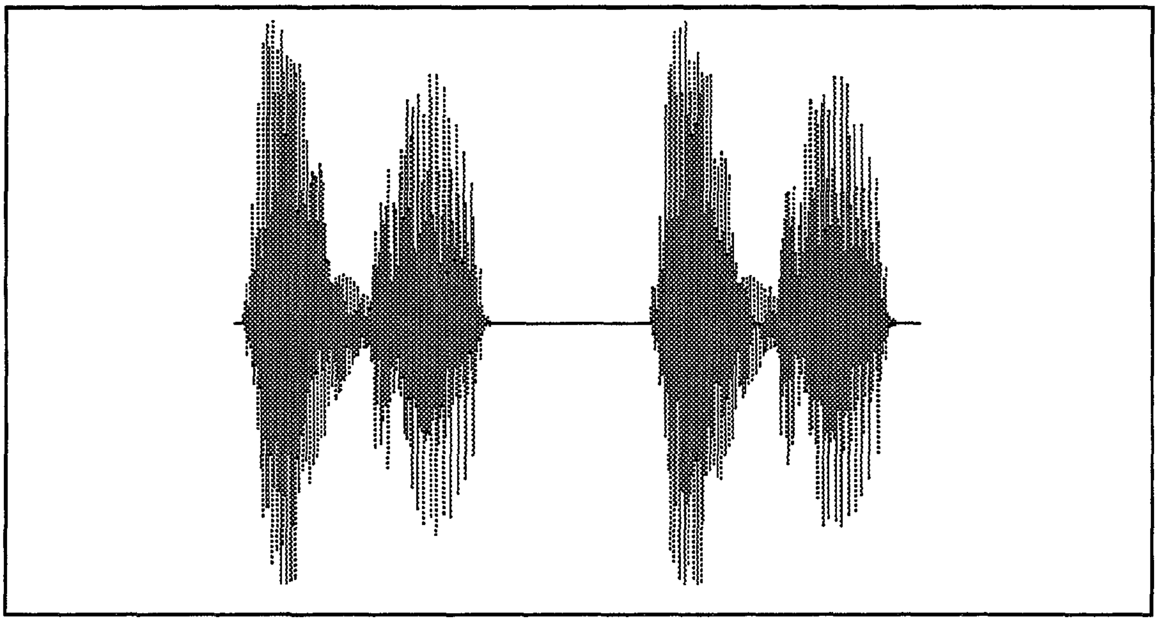

Figure A-5. Time-series plots for Sound 4: Male Digitized Voice.

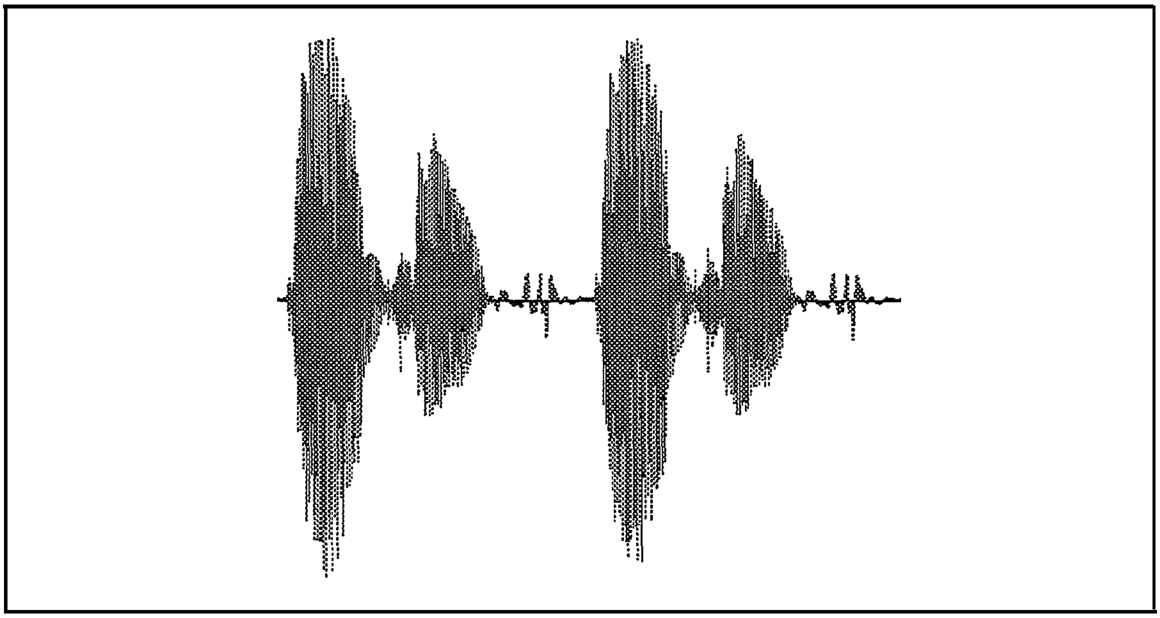

Figure A-6. Time-series plot for Sound 5: Female Digitized Voice.

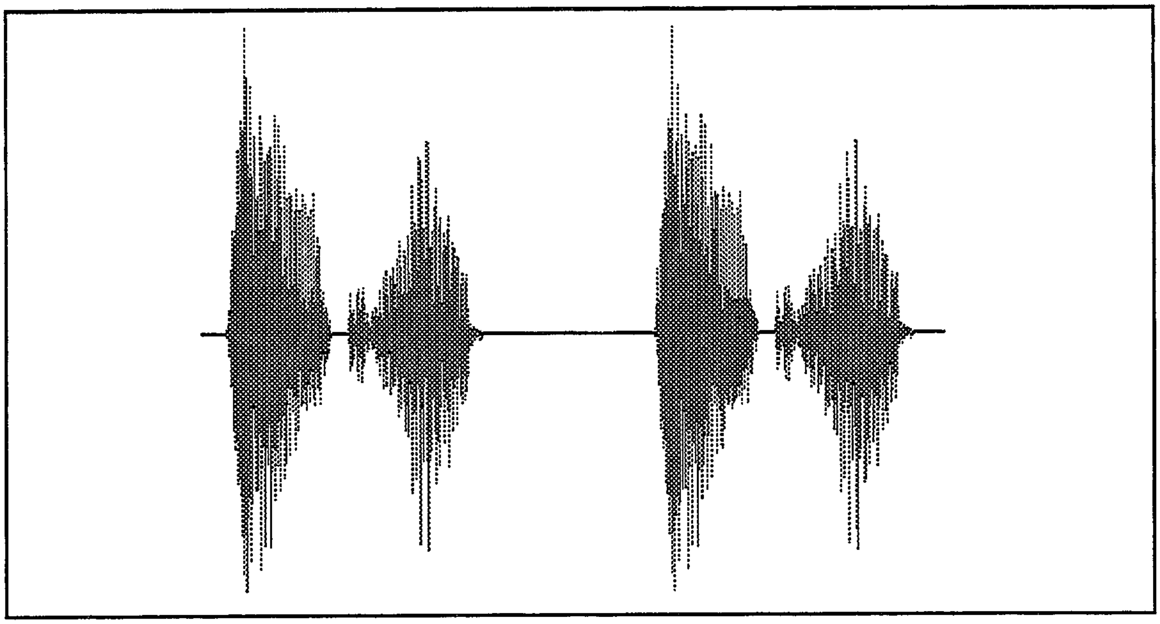

Figure A-7. Time-series plot for Sound 6: Male Synthesized Voice.

APPENDIX B

AUDIOMETRIC HEARING TEST DATA

TABLE B-l

Subject Hearing Test Data for Younger Age Group

					Pure-Tone Freauencv (Hz)					
Age	Gender	Ear	250	500	1000	2000	3000	4000	6000	8000
21	F	L	20	10	10	0	0	5	5	0
		R	15	10	5	0	0	10	0	5
29	F	L	10	10	5	0	0	0	5	0
		R	10	10	10	0	0	0	0	0
20	F	L	15	10	10	10	0	10	10	15
		R	20	15	‘10	10	15	10	10	10
22	F	L	10	10	5	5	5	0	5	10
		R	10	10	5	0	5	10	10	5
22	F	L	5	10	10	0	0	0	5	5
		R	5	10	10	0	0	5	0	5
29	F	L	35*	25*	30*	10	30*	15	25*	35*
		R	25	20	20	10	10	10	10	10
32	M	L	15	10	0	5	5	15	10	10
		R	15	15	5	0	0	5	10	5
27	M	L	20	20	10	0	5	5	15	10
		R	15	15	5	5	5	5	10	0
21	M	L	5	0	0	0	0	0	10	5
		R	0	5	0	0	0	0	5	0
31	M	L	5	0	0	0	5	5	5	0
		R	10	5	0	0	5	10	0	5
23	M	L	0	0	0	0	0	10	0	10
		R	5	0	0	10	0	0	0	10

21	M	L	10	5	5	0	5	5	5	0
		R	5	0	10	0	10	0	5	5

TABLE B-2

Subject Hearing Test Data for Mature Age Group

			Pure-Tone Frequency (Hz)							
Age	Gender	Ear	250	500	1000	2000	3000	4000	6000	8000
65	F	L	25	15	10	15	20	25	45	55
		R	25	20	15	30	25	25	45	60
70	F	L	10	10	10	15	35	15	50	45
		R	15	5	10	25	25	5	50	40
68	F	L	30	20	20	20	35	45	35	40
		R	15	20	15	25	40	50	50	55
72	F	L	10	5	10	15	10	5	15	20
		R	15	5	20	20	10	10	20	45
73	F	L	20	15	25	20	30	40	40	60
		R	15	15	25	45	35	35	50	55
71	F	L	30	25	20	10	20	40	65	75
		R	25	25	10	15	20	30	60	80
70	M	L	20	15	10	10	20	35	40	50
		R	15	20	20	10	20	30	35	55
66	M	L	5	20	20	20	0	10	15	30
		R	15	15	20	15	0	10	20	20
68	M	L	35	35”	10	0	10	15	15	25
		R	5	0	0	20	10	20	20	25
65	M	L	15	10	20	30	45	45	65”	60
		R	15	25	20	40”	55”	45	70”	55
70	M	L	30	30	20	10	15	25	65	70
		R	35	30	35	10	20	40	60	70

70	M	L	20	20	15	20	30	35	50	65
		R	10	20	10	30	45	55	75	80

APPENDIX C

INFORMED CONSENT FORM

CONSENT FORM
LOCALIZATION OF IN-VEHICLE WARNINGS

Purpose of the Research: The purpose of this research is to determine how well driver's can detect the direction of sounds presented within a car. Warning sounds presented from various locations in a car may be incorporated with new warning systems, such as a system that would alert the driver of objects in his or her "blind spot" or of objects behind the vehicle that the driver may not be aware of. Under contract with the National Highway Traffic Safety Administration (NHTSA), COMSIS is investigating the effectiveness of auditory warning localization in vehicles through studies such as this one. Your feedback will help to determine guidelines for the development of in-vehicle crash avoidance warning alarms.

Research Procedures: In this experiment, you will sit in the drivers seat of a parked car and will be asked to listen for warning sounds in a background noise while watching a video tape of a driving scene. Each time you hear a sound you will indicate the direction of its source by pushing the joystick in the direction of the sound. Once you are satisfied with the direction you pushed the joystick, you will need to hold the joystick there and press the button on the top of the joystick to register your response. You should make your response as soon as you have determined the sound's direction.

In addition to these tasks, each time the camera car passes over or under a bridge (i.e., an over-pass or under-pass) you will verbally respond by saying "BRIDGE". Your response will be recorded through a microphone. As a bonus for responding "BRIDGE" to all of the over-passes and under-passes during the video taped drive, you will receive an additional five dollars ($5) at the end of the experiment. You will be allowed to miss 25% of the total number of bridges and still receive the bonus.

Foreseeable Risks: There are no unusual risks associated with participating in this study, other than those normally associated with being in an office environment and parking garage--where the vehicle is parked. All sounds and noises that you hear are below the Occupational Safety and Health Administration (OSHA) sound level regulations (i.e. volume levels) for noise in order to protect your hearing.

Benefits of the Research: The findings of this study will be used to develop guidelines for the development of in-vehicle warning systems. As a result of the research, the effectiveness of presenting warnings from various directions around the driver will be determined. In conjunction with other research in this area, the development of a warning system which presents sounds from different directions could result in a driving environment that is more safe, comfortable, and usable by the full range of the driving public.

You will be paid $40 for your participation in the experiment, as well as a bonus of $5 if you complete the "bridge spotting" task successfully (total of $45 possible). If the investigator must terminate the session earlier than planned, you will be paid the maximum amount of $45.

Confidentiality: We will ask to look at your drivers license to confirm your age and your driving status, ask how long you have been driving, and how often you drive. You should also have received a hearing test by this time to confirm your eligibility to participate in this study. All of this information is confidential, and no published reports of the research will identify any participant. Likewise, all information collected during the study is confidential and will not be presented in any form that identifies individuals.

Contact Person: If you have any questions about the research or the rights of research participants, you may contact Dr. Neil Lemer, Project Manager, Human Factors and Safety, COMSIS Corporation, 8737 Colesville Road, Silver Spring, MD 20910; [telephone (301) 588-0800].

Voluntary Withdrawal from the Experiment: Your cooperation in this study is entirely voluntary. You may withdraw participation for any reason at any time. If you withdraw from the study, you will be paid on a prorated basis for the portion of the study you completed.

AUTHORIZATION: I have read the above and recognize the risks of this study. I agree to participate as a subject in the research. I also understand that participation is voluntary and I may withdraw from the study at any time.

Signature of Participant: ______________________________ Date: ______

(printed name): ______________________________

Signature of Investigator: ______________________________ Date: ______

FOR OUR RECORDS

Address: ____

____

DOB: ______________________

If you are interested in being contacted occasionally for further research please leave your phone number below:

____

APPENDIX D

VERBAL INSTRUCTIONS

INSTRUCTIONS FORM

LOCALIZATION OF IN-VEHICLE WARNINGS

(To be read by experimenter to subject)

INTRODUCTION

You may have a seat here in the car. Just watch your head as you get in. The purpose of this research study is to help determine the effectiveness of presenting warning sounds from different directions around the driver. In today's study, we are interested in your ability to determine the direction of sounds in a car as you sit in the driver's seat and watch a video tape of a road scene. Do you have any questions? Before we continue, I'll need you to read and sign this consent form, and this will give you some information about the procedure we'll follow.

CONSENT FORM

[Hand out and explain informed consent forms]

{Ask if there are any questions]

ADJUST HEAD POSITION

Before I familiarize you with what you will have to do during this study, I will need to adjust your seating position. After you are seated properly, I will show you what you will need to do.

[ADJUST HEAD POSITION]

PROCEDURE (Subject seated in vehicle)

In this experiment, you will sit in the driver's seat and will be asked to listen for warnings sounds in a background noise while watching a video tape of a driving scene. Each time you hear a sound you will indicate the direction of the sound by pushing the joystick (that's mounted here) in the direction of the sound. Once you are satisfied with the direction you pushed the joystick, you'll need to hold the joystick in that position and press the red button on the top of the joystick to register your response. The sound that you hear will be presented from an infinite number of directions. As such, the joystick can also be pushed in an infinite number of directions.

As soon as you have determined the sounds direction, you should make your response as quickly and as accurately as possible.

In addition to these tasks, each time the camera car passes over or under a bridge (Le., an over-pass or under-pass) you will verbally respond by saying "BRIDGE". Your response will be recorded through a microphone mounted on the steering wheel. As a bonus for responding "BRIDGE" to all of the over-passes or under-passes encountered during the video taped drive, you will receive an additional five dollars ($5) at the end of the experiment. You will be allowed to miss 25% of the total number of bridges and still receive the bonus. If you are unsure about whether something you see on the video constitutes a bridge, respond "BRIDGE" anyway. You will not be penalized for responding at the wrong time.

[ASK IF THERE ARE ANY QUESTIONS]

DESCRIBE TASKS

You will also listen for warning sounds presented from different directions around you. When you hear a sound, you will use the joystick positioned next to you to indicated the direction of the sound.

You may quickly glance or turn your head *slight/y towards the genera/ direction of the sound in order to determine it's location, but don't turn your upper body to face the direction of the sound. In addition, always face forward when making the actual response and try not to miss any bridges.*

[ASK IF THEY ARE FAMILIAR WITH USING A JOYSTICK]

JOYSTICK

To use the joystick you will need to push the joystick handle in the direction of the sound. After you have positioned the handle in the proper direction, you will then have to press the red button on the top of the joystick handle to register your response. You *should make your response as soon as you have determined the sound's direction. Also, keep in mind that the sound will appear from an infinite number of directions and the joystick will accept any direction you push the handle.*

!!To prevent accidentally pressing the button <u>before</u> you have positioned the joystick in the desired position, please do not keep your finger on the button. Only place your finger in position when you are ready to press the button.

[ASK SUBJECT TO FAMILIARIZE THEMSELVES WITH JOYSTICK MOVEMENT]

During the experiment, the sounds you will be listening for will remain on until you position the joystick and press the button on the joystick. After your response is registered, the sound will be automatically turned off. If the sound does not turn off after you press the button, the computer did not register your response. If this happens, make sure the joystick is in the position you want and the press the button again. Also, do not continue to hold the button down after the sound is turned off.

After your response is registered, always return the joystick handle to it's center position--it will automatically go back to this position if you let go of the handle. In addition, do not move the handle until after a sound is presented. If you accidentally move the joystick before a sound is presented, the computer will wait until the handle is returned to the center position. If this occurs, I will ask you to return the handle to the center position through a speaker mounted near the joystick. Sometimes I may ask you to center the joystick even if the joystick appears to be centered. In this event, please push the joystick in any direction and return it to the center position.

The sounds will be randomly presented to you one after the other at random intervals. You will have to be ready to respond to the next sound after making a response, so please be ready at all times. If you are unsure about the direction of the sound, just try and make your best guess. There are no wrong answers in this experiment.

[ARE THERE ANY QUESTIONS ABOUT WHAT YOU ARE TO DO?]

When we perform experiments involving simulated driving, we try to make the driving experience seem as realistic as possible. One of the ways we're going to make the study today realistic is by playing a background noise that sounds like the interior of a car that is driving on a highway. Also, when people are really driving, they need to respond to things on the road. What we're going to ask you to do is to respond to every bridge that you see. Each time you see a bridge on the video tape, you should say "BRIDGE" loud enough so that a person sitting next to you would be able to hear you in the noise--you *do not have to speak into the microphone.* If you are unsure about whether something you see on the video constitutes a bridge, respond "BRIDGE" anyway. You will not be penalized for responding at the wrong time. Let me demonstrate what do when you see a bridge on the video tape.

[SHOW DEMO TAPE AND WHEN TO SAY "BRIDGE"]

Can you see the TV clearly?

Do you need me to adjust the seat position to help you see it better?

[ARE THERE ANY QUESTIONS]

EXPERIMENT SEGMENTS AND BREAKS

The experiment will consist of a practice session and three data collection sessions. A five minute break will be given between each data collection session. In addition, a calibration routine will be required at the beginning of the practice session and at the beginning of each of the data collection sessions.

CALIBRATION ROUTINE

Everyone is different, and calibration is required to determine the positions of the joystick that you feel correspond to different parts of the car. During the calibration session, I will ask you to push the joystick in a specified direction--you will not be presented with the video or hear the background noise and warnings sounds during this procedure; however, you will hear my voice through the speaker mounted near the joystick as I give you instructions.

For example, during calibration I might ask you to push the joystick to signify a direction directly to your right or to your left. Once you have positioned the joystick in this direction, you will then need to press the red button on the top of the joystick--remember that it is important that you do not keep your finger on the button. In addition, please try and keep your head facing forward as you make your response. Just like during the experiment, you may quickly glance or turn your head slightly towards the direction specified in order to determine the specified location, but always face forward when making the actual response. You will be asked to make a response for 24 directions. Each calibration routine will take approximately 5 minutes.

[ARE THERE ANY QUESTIONS?]

Once a data collection segment is begun, you will not be allowed to ask questions since the segment cannot be interrupted, so please ask any questions you have now or during one of the breaks. However, you may stop the procedure at any time if you feel that you would like to withdraw from the study. You know, the interiors of different cars are set up differently, so I just wanted to point out the door handle to you to open the door if you need to. You won't need to touch any of the other controls for the car. Also, I can turn the car's fan on for you. Would you like me to turn it on for you? [IF PARTICIPANT DOES NOT WANT FAN ON NOW] - OK, but just let me know during one of the breaks if you'd like me to turn the fan on.