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Increasing Truck Driver's Awareness: Use of In-Vehicle 3D Sounds

Final Report for
Safety IDEA Project 19

Prepared by:
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1. EXECUTIVE SUMMARY

This report describes the results and conclusions of "Increasing Truck Driver's Awareness: Use of In-Vehicle 3D Sounds," a Safety IDEA project aimed at developing and testing a system using in-vehicle three-dimensional (3D) sound as a technique for augmenting the truck driver's situational awareness (SA). Sound insulation of the truck cab, designed to reduce noise, vibration, and harshness (NVH), coupled with the inherent limited visibility from inside the truck cab, can contribute to the reduction in the driver's SA around the truck. The objective of this project was to test whether 3D sounds could be used effectively to increase the driver's SA by providing traffic cues, i.e., different simulated traffic situations represented by auditory icons. Auditory icons are sound representations of real world, naturally occurring events. Icons representative of four road users (cars, bicyclist, pedestrians, and motorcycles) that a truck driver would typically encounter in traffic situations, were created and used to determine if a 3D sound system can increase the driver's awareness of the traffic situation by hearing the road user's location, and directional movement relative to the driver's position in the vehicle.

The investigation to implement, optimize, and test an in-vehicle 3D sound system was organized into two stages. Stage I consisted of creating and testing natural sounding 3D auditory icons. Test clinics were conducted in order to determine if participants could:

- Recognize the 3D auditory icon (cue recognition) by matching the 3D sound to the representative road user (cars, bicyclist, pedestrian, and motorcycle).
- Determine the road user's location (cue detection) by matching the 3D sound to the sound source location.
- Determine the road user's direction of movement (cue projection) by indicating the spatial movement of the 3D sound.

In analyzing recognition accuracy, auditory icons resulted in high accuracy rates which indicate their intuitiveness and high degree of association to the intended object. The results also indicated that spatial movement, coupled with the context of a traffic scenario where a safety critical event could occur between truck and road-users, tended to increase the accuracy to assess situational awareness.

Based on the results of Stage I, Stage II consisted of integrating the optimized 3D sound system into a truck cab in order to evaluate the effectiveness of the sound icons while conducting actual driving maneuvers. The driving clinic was conducted on a test course that was designed to simulate a suburban neighborhood delivery scenario. The results of Stage II indicated that, when analyzing recognition accuracy, auditory icons resulted in high accuracy rates , thus demonstrating the potential to effectively use 3D sounds, under realistic driving conditions. All of the participants in this pr oject commented that they felt that this type of system could be beneficial. However, there are concerns associated with disguishable sounds that are not impacted by other in-vehicle cab sounds, too many alarms/alerts associated with other vehicle systems increasing their annoyance levels, and the possibility of other potential interfaces (vocal/spoken word alert, visual display alert, etc.). These indicate areas where future investigation and technological advancements will be needed in order to integrate 3D sounds into production vehicles.

2. THE PRODUCT

The objective of this project was to develop and test a system using in-vehicle three-dimensional (3D) sound as a technique for augmenting the truck driver's situational awareness (SA). In the driving task, vision, hearing, and the haptic senses are all used by the driver to gather information concerning traffic and road environment conditions surrounding the truck. However, in-vehicle sounds due to wind, cooling fans, road surfaces, the engine, vibrations, tires, and exhaust, typically referred to as noise, vibration, and harshness (NVH), can be disturbing (Mortimer, 1994; van den Heever and Roets, 1996), and result in sound levels in the vehicle cab that are high enough to cause permanent hearing loss (Reif et al.,1980). These high noise levels can lead to distractions, which have been found to negatively impact driver performance and safety. For these reasons, commercial vehicle manufacturers, such as Volvo, have focused on a wide range of noise reduction features for their trucks, all designed to keep cabin sound levels low, including vehicle cab insulation for sounds from surrounding traffic, since many of our vehicles are designed to provide living/resting accommodations. However, sound insulation of the truck cab, along with the inherent limited visibility from inside the truck cab, can contribute to the reduction in the driver's SA around the truck.

The objective is to test whether 3D sounds could be used effectively to increase the driver's SA by providing traffic cues, i.e., different simulated traffic situations represented by auditory icons. Auditory icons are sound representations of real world, naturally occurring events. Icons representative of four road users (cars, bicyclist, pedestrians, and motorcycles) that a truck driver would typically encounter in traffic situations, will be used in order to determine if a 3D sound system can increase the driver's awareness of the traffic situation by hearing the road user's location, and directional movement relative to the driver's position in the vehicle. The anticipated product to be developed is intended to provide a system that can be integrated into a truck cab in order to provide simulated traffic cues to improve the truck driver's traffic awareness around the truck under naturalistic driving conditions, and contribute to increased safety of trucks and road users near and around the truck.

3. CONCEPT AND INNOVATION

3.1 SITUATIONAL AWARENESS

Situational awareness (SA) is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1995). SA encompasses three of the important aspects of driving performance (perception, comprehension, and projection), and has been found to be critical to decision making in complex tasks (FIGURE 1).

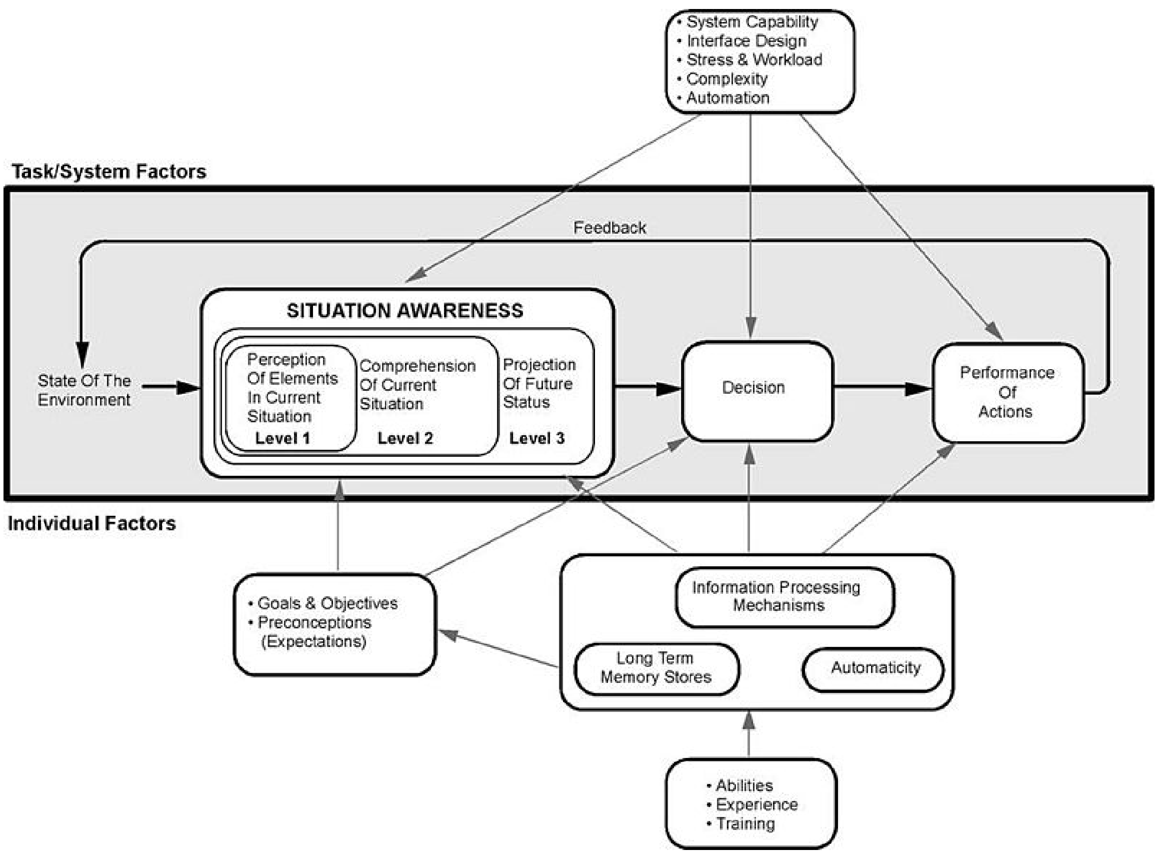


FIGURE 1 Model of situation awareness in dynamic decision making (Endsley, 1995).

Perception (Level 1 SA): The first step in achieving SA is to perceive the status, attributes, and dynamics of relevant elements in the environment. This involves the processes of monitoring, cue detection, and simple recognition, which lead to an awareness of multiple situational elements (e.g., road users) and their current states (locations, conditions, modes, actions).

Comprehension (Level 2 SA): Using the perceived information gathered, comprehension integrates this information to understand how it will impact upon the individual's goals and objectives.

Projection (Level 3 SA): The highest level of SA involves the ability to project, and anticipate the future actions of the elements in the environment. Level 3 SA is achieved through knowledge of the status and dynamics of the elements and comprehension of the situation (Levels 1 and 2 SA), and then extrapolating this information forward in time to determine how it will affect future states of the operational environment.

Driving is a complex task requiring perception, comprehension and projection of states of the roadway environment, as well as decision making on courses of action and execution of driving behaviors. Ward (2000) and Matthews et al. (2001) related the levels of SA to specific driving tasks, including operational, tactical and strategic behavior. We develop a mental strategy based on enhancing how to look (perception), using scanning strategies to increase the perception of relevant information. In order to interpret what we see (comprehension of the information), an accurate understanding of the current situation is needed, and requires continuous thought about the environment and actions we have made. Then combining the first two processes, we derive the meaning of what we see (projection) in a way that increases our anticipation of a potential safety critical event. Anticipation is how we begin to see accidents before they happen and make good decisions in order to carry out defensive actions. The question of this project is to determine whether 3D sounds can augment and or increase the driver's SA (at multiple levels) while performing driving tasks.

3.2 USE OF 3D SOUNDS

While the driving task is primarily visual, the driver also utilizes auditory cues. Sound has been found to be a very efficient means of providing warnings and information in vehicles, especially in situations where the visual modality may be limited or overloaded due to distractions. However, typically the central characteristic of most in-vehicle auditory warnings is non-directional, with the goal of conveying an appropriate level of urgency. The goal of this research is to determine if in-vehicle sounds, in particular 3D sounds which provide spatial information, provides information to augment SA, which is obtained primarily via visual scanning. So instead of providing arousal to convey a level of urgency associated with warning or alerts, can sounds be used to provide cues to augment SA?

Preliminary work has indicated the potential of spatial or 3D auditory icons. Faller et al (2005) found that for subjects with visual impairments, there was higher accuracy in icon selection when guidance information was provided by 3D sounds icons in the computer interface navigation process. Larsson et al (2009) found that in informing and warning the truck driver of vulnerable road users (pedestrians, cyclists, small vehicle motorists, etc.) near and around the truck, 3D sounds were more efficient/urgent than mono sounds. By combining sound icons and 3D information it is likely that one can rapidly and efficiently convey the sensation that something dangerous is approaching from a certain direction (using 3D directional cues), leading to more rapid and correct action. There was also a high acceptance and satisfaction of use among truck drivers, as the participants associated the 3D sound with something outside the truck (an approaching and potentially dangerous situation) while the mono sound was associated with their own truck horn i.e. something less urgent.

4. INVESTIGATION

The investigation to implement, optimize, and test an in-vehicle 3D sound system was organized into two stages. Stage I consisted of creating and testing natural sounding 3D auditory icons. Auditory icons are sound representations of real world, naturally occurring events, so they are typically considered to be intuitive, with each icon representing a single object or action (Hempel and Altinsoy, 2005). Icons representative of four road users (cars, bicyclists, pedestrians, and motorcycles) that a truck driver would typically encounter in traffic situations, were designed. Test clinics were conducted in order to determine if participants could:

- Recognize the 3D auditory icon (cue recognition) by matching the 3D sound to the representative road user (cars, bicyclist, pedestrian, and motorcycle).
- Determine the road user's location (cue detection) by matching the 3D sound to the sound source location.
- Determine the road user's direction of movement (cue projection) by indicating the spatial movement of the 3D sound.

Based on the results of Stage I, Stage II consisted of integrating the optimized 3D sound system into a truck cab in order to provide the 3D auditory icons under realistic driving conditions.

4.1 STAGE I

4.1.1 3D Auditory Icons – Sound Design

Icons representative of four road users (cars, bicyclists, pedestrians, and motorcycles) that a truck driver would typically encounter in traffic situations, were designed in order to determine if a 3D sound system can increase the driver's awareness of the traffic situation by hearing the road user's location, and directional movement relative to the driver's position in the vehicle. Based on guidance from SAE J2830 (2008), additional synthetic icons, i.e., earcons (Blattner et al., 1989) were also designed representing the road users in order to provide comparison data. Three sound themes were designed for sounds representing the road users; cars, bicyclists, pedestrians, and motorcycles:

- Natural sound – sounds, representing real events that have been designed to have a high degree of association to the intended object (icon).
- Enhanced natural sound – natural sounds that have been enhanced by means of filtering and adding sound components (earcon).
- Synthesized sound – sounds synthesized with the intent to provide a level of familiarity of their source object.

4.1.2 Experimental Setup

The equipment and programs used for testing included:

- Windows 7 equipped Dell Latitude D620 Laptop computer
- Diamond Xtreme Sound USB External Sound Card (Digital HD 7.1)
- Logitech Surround Sound Speakers Z506 (4 Satellite, 1 center, 1 sub-woofer)
- Bamboo Create USB Tablet
- Volvo Group Truck Technology Custom Sound Control Program (survey application)
- Condenser Microphone
- Orban Loudness Meter Software

The testing was conducted in a conference room that allowed good isolation of the test participants from distractions. The room was approximately 18' x 12' and the speakers were arranged around the test subject's seat, as shown in FIGURE 2. A microphone was attached to the top of the seat back and a test sound file was swept around all speakers. The level for each speaker was adjusted using the Diamond Xtreme Sound Card configuration program. The sound level was monitored using the Orban loudness meter software. The level from each speaker was calibrated to peak sound intensity level of 70dBA which was chosen to be the maximum loudness of the system.

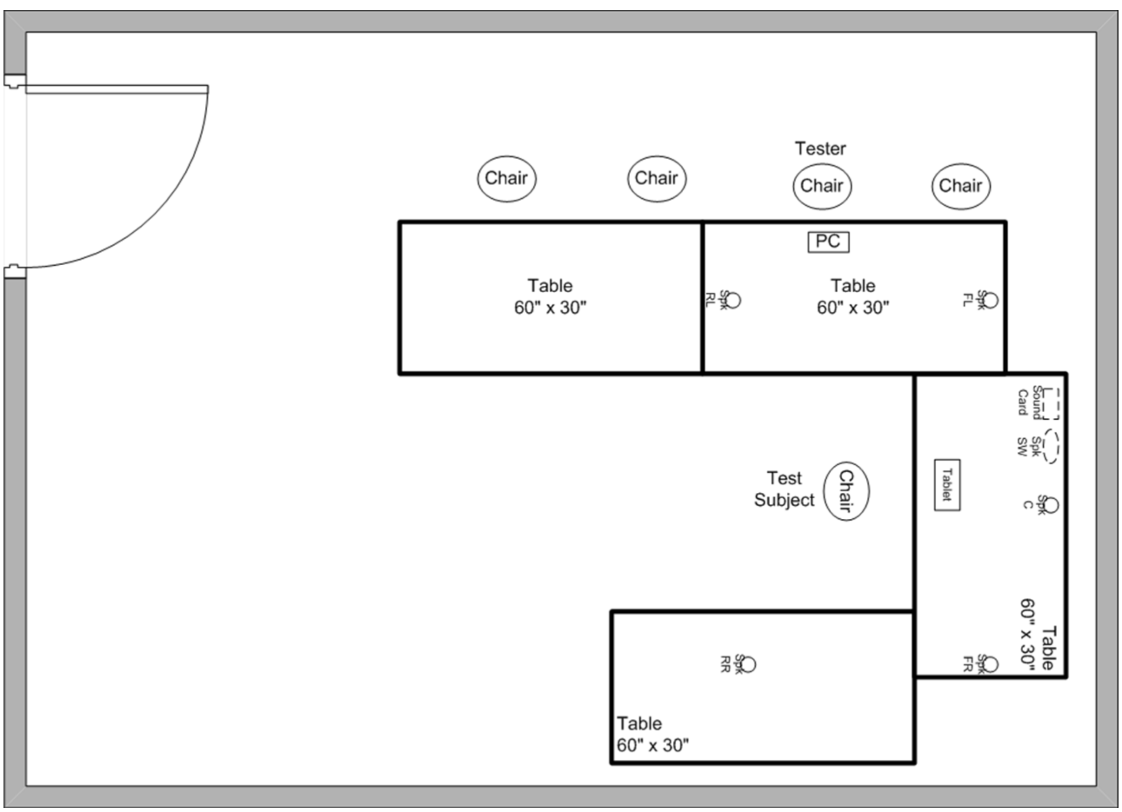


FIGURE 2 Experimental setup for testing.

4.1.3 Participants

A total of nine participants were recruited for the study. There were six males and three females, with an average age of 46 years. Three of the participants had a commercial driver's license (CDL).

Before the participants arrived to the test, they received background information concerning the purpose and objective of the testing. Upon their arrival, the background and purpose of the testing was reviewed with the participants. They were then instructed concerning the details of the equipment setup (FIGURE 3), and shown how to provide their test responses using the Bamboo Create tablet and pen on the table directly in front of them. Each test clinic (three in total) used a different graphic under a transparent sheet that laid on the tablet's surface. Feedback from the participants was gathered by a pen's movements on the tablet's surface. The custom Volvo software used the Diamond Audio card to send sounds to the 5.1 speakers and also recorded the tablet based responses.

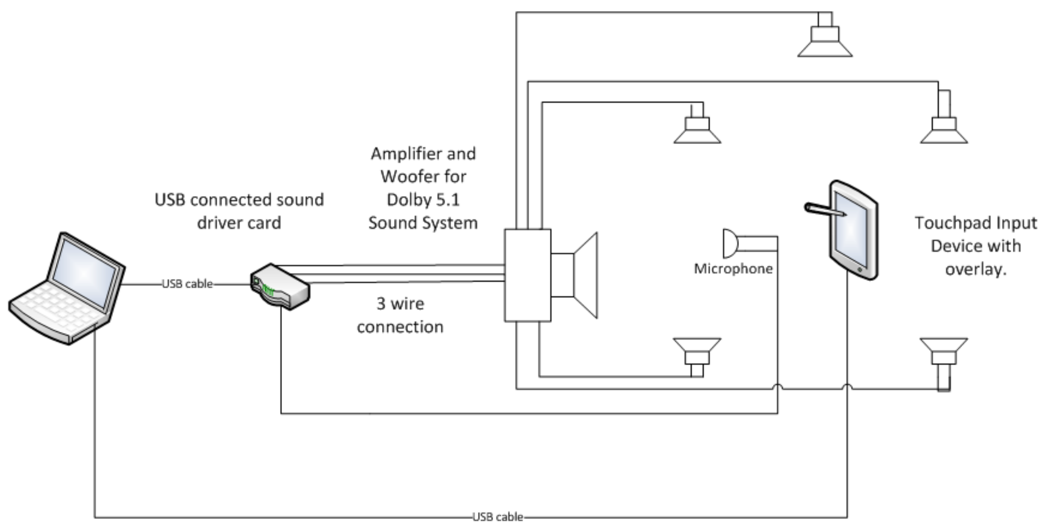


FIGURE 3 Model of equipment used to emit sounds, and record participants responses.

4.1.4 Test Clinics

The test was conducted in three sections that were referred to as clinics. A written instruction page was presented to the subject for each clinic and any questions about the expectations of the test were addressed.

A repeated measures design was used for each clinic. All of the participants were tested with each of the three sound themes (natural, enhanced, and synthesized) for all sounds representing the road users (cars, bicyclists, pedestrians, and motorcycles). All test trials were randomized for each participant.

4.1.4.1 Clinic 1: Cue Recognition

Clinic 1 addressed the first level of situational awareness (SA), perception, in particular cue recognition. The focus of the clinic was to assess the recognition of the 3D auditory icons and earcons. Using SAE J2830

(2008) as guidance, participants were instructed to match the 3D sound to the representative road user (cars, bicyclist, pedestrian, and motorcycle).

The participants were presented with a series of 3D sound representations of the road users (cars, bicyclists, pedestrians, and motorcycles), all rendered in the three sound themes (natural, enhanced natural, and synthesized). They were instructed to quickly identify the road user that the sound represented by using the tablet pen to press/choose the icon indicated on the tablet (FIGURE 4). They were allowed to respond by choosing either the left and/or right side icon depictions. The 3D sounds were played through the speakers in a clockwise rotation pattern around the participant for 15 seconds, and a feedback click sound provided the indication that the icon had been selected. After 15 seconds, the sound stopped, there was a 5 second pause, and then the next sound was presented indicating the beginning of the next trial. All participants were provided with a demonstration of the procedure to illustrate the type of sound that they would be hearing, and how to record their responses (the demonstration presented a random 3D sound did not represent any of the 3D auditory icons/earcons being tested).

FIGURE 4 Clinic 1 tablet overlay used to record participants responses.

4.1.4.2 Clinic 2: Cue Detection (Location)

Clinic 2 addressed the levels 1 (perception) and 2 (comprehension) of situational awareness (SA). The focus of the clinic was to assess the location of the 3D auditory icons/earcons sound source.

The participants were presented with a series of 3D sound representations of the road users (cars, bicyclists, pedestrians, and motorcycles), all rendered in the three sound themes (natural, enhanced natural, and synthesized). They were instructed to quickly identify the location of the sound, using the tablet pen to indicate the source sound location relative to their location (marked as "X" on the tablet overlay – FIGURE 5). To produce a natural impression of sound source distance to the participant, the sound system attenuated the sounds as they move farther away from the position relative to the participant according to the inverse square law.

The 3D sounds were played through the speakers for 15 seconds, and feedback click sounds were provided to indicate that the location, and icon, had been selected. After 15 seconds, the sound stopped, there was a 5 second pause, and then the next sound was presented indicating the beginning of the next trial. All participants were provided with a demonstration of the procedure to illustrate the type of sound that they would be hearing, and how to record their responses (the demonstration presented a random 3D sound did not represent any of the 3D auditory icons/earcons being tested).

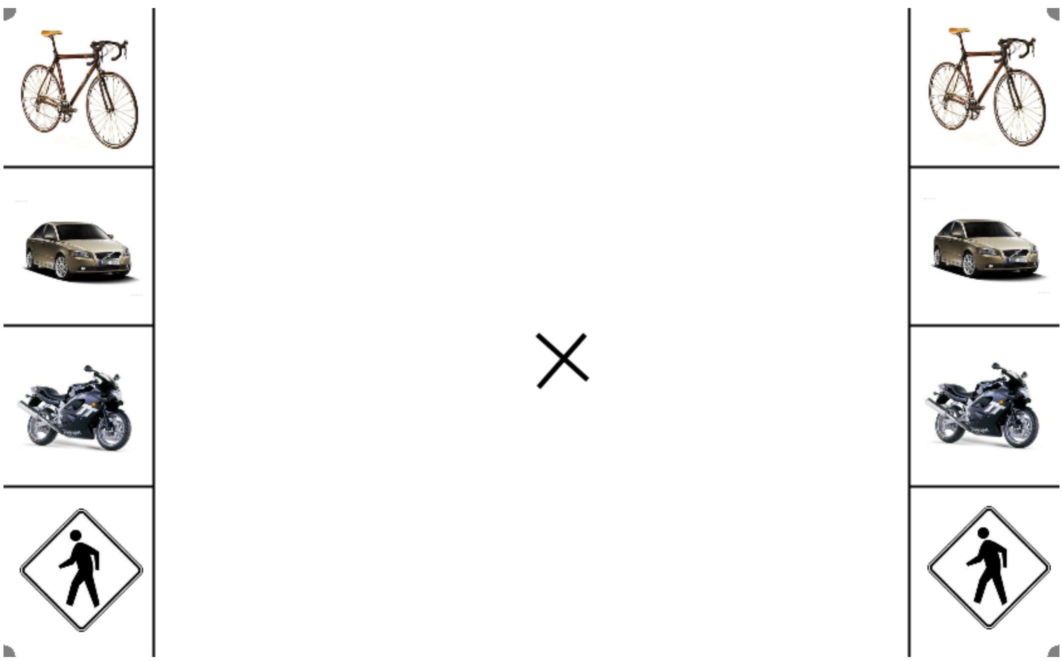


FIGURE 5 Clinic 2 tablet overlay used to record participants responses.

4.1.4.3 Clinic 3: Cue Projection (Dynamic Movement)

Clinic 3 addressed all three levels of situational awareness (SA). The focus of the clinic was to assess the direction of movement of the 3D auditory icons/earcons sound source. The participants were given the context of a traffic scenario where a safety critical event could occur between truck and road-users are likely to occur due to the truck driver's limited view. They were given the following context (FIGURE 6):

"The illustrated traffic scenario is based on you, as the truck driver, making a right turn on the green light. You will be presented with a series of 3D auditory sound representations of the following road users: car, cyclist, pedestrian(s), and motorcycle. The sound will be played in two cycles. As quickly as you can, indicate first, the direction of the sound, by pressing the start location, dragging and then lifting the pen within the scenario space on the tablet in the direction of movement on the illustrated traffic scenario."

The sound system attenuated the sounds based on their direction of movement relative to the participant according to the inverse square law.

The 3D sounds were played through the speakers for 15 seconds in two cycles, and feedback click sounds were provided to indicate that the direction of movement, and the icon, had been selected. After 15 seconds, the sound stopped, there was a 5 second pause, and then the next sound was presented indicating the beginning of the next trial. All participants were provided with a demonstration of the procedure to illustrate the type of sound that they would be hearing, and how to record their responses (the demonstration presented a random 3D sound did not represent any of the 3D auditory icons/earcons being tested).

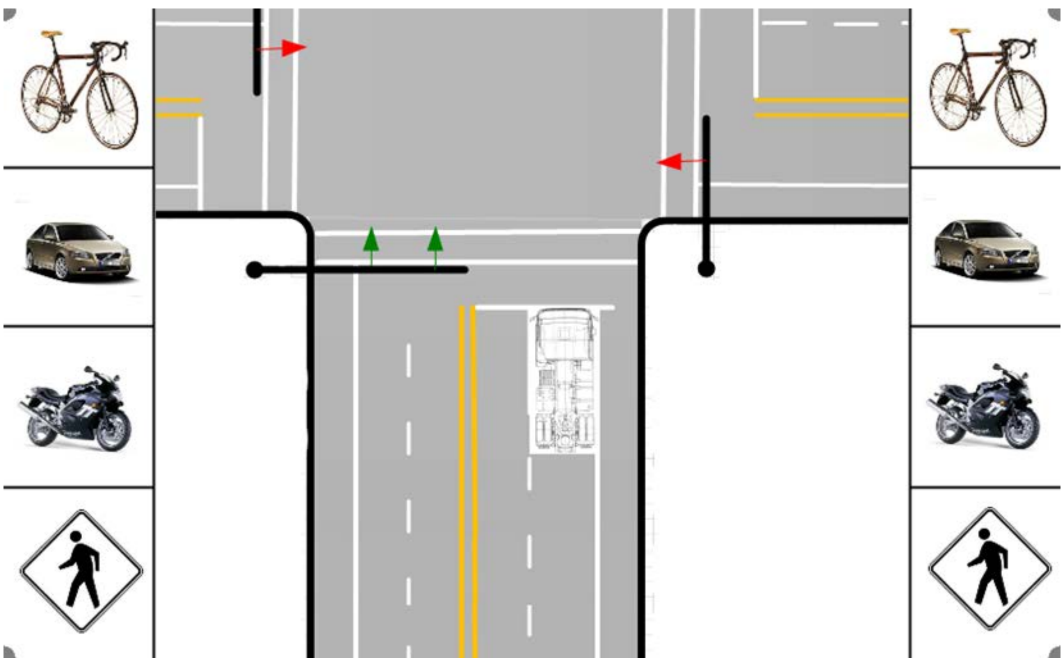


FIGURE 6 Clinic 3 tablet overlay used to record participants responses.

4.1.5 Results

4.1.5.1 Clinic 1 Results

Data gathered from clinic 1 was analyzed to assess the performance in recognizing the 3D auditory icons and earcons. The analysis focused on the hit-ratio (percentage of correct selections of the icon/earcon in each trial), and the response time of the correct selection of the icon/earcon. The hit-ratio percentage represents the accuracy of recognition, while the response time indicates length of time required to perceive the icon/earcon. The performance goal is high accuracy coupled with a low response time.

In analyzing the accuracy of recognizing the icon/earcon, the natural sound theme (icon) had the highest accuracy rate, which indicates a level of intuitiveness and high degree of association to the intended object (FIGURE 7). High recognition accuracy rates were also associated with the enhanced natural sounds (earcon). However, there was a noticeable decrease in accuracy associated with the synthesized sounds (earcon).

Road User	Sound Theme	Hit Ratio (%)
Bike	Enhanced	100
	Natural	100
	Synthesized	94
Car	Enhanced	85
	Natural	100
	Synthesized	33
Motorcycle	Enhanced	100
	Natural	100
	Synthesized	77
Pedestrian	Enhanced	100
	Natural	100
	Synthesized	72

FIGURE 7 Clinic 1 – Hit Ratio Results.

Similar results were found with the analysis of the mean response times (FIGURE 8) where the length of time required to perceive the natural and enhanced natural sounds was lower than the synthesized sounds.

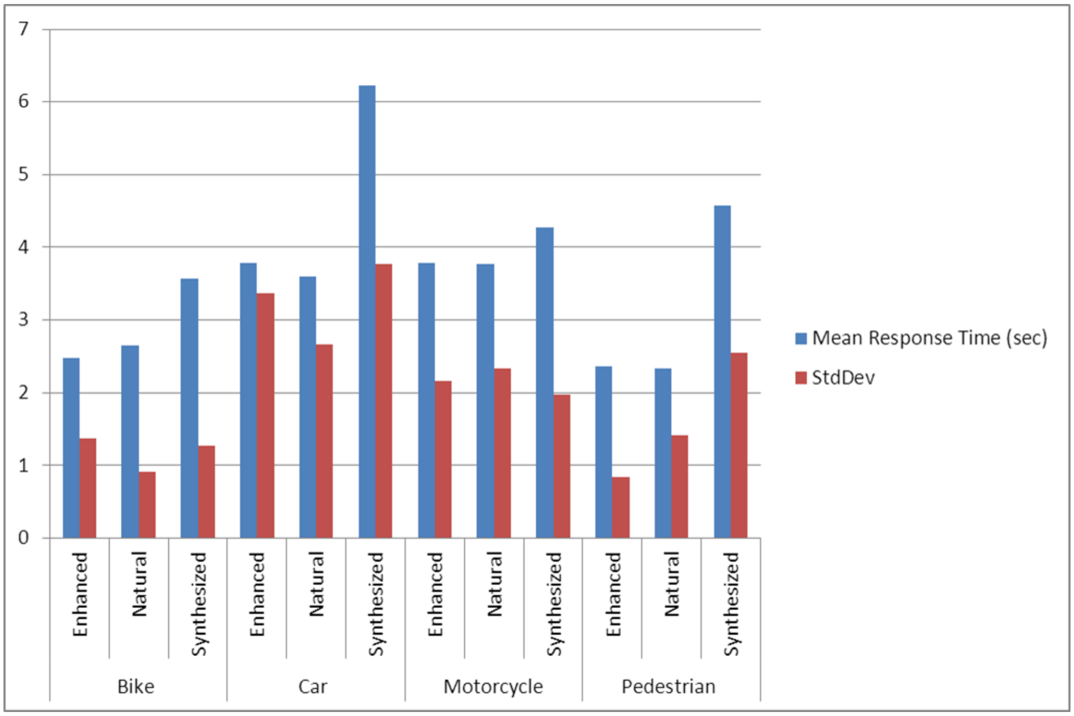


FIGURE 8 Clinic 1 – Mean Response Time Results.

4.1.5.2 Clinic 2 Results

Data gathered from clinic 2 was analyzed to assess the location of the 3D auditory icons/earcons sound source. The analysis focused on the angular deviation between the sound source location and the participants' indication of the location. The performance goal is a low angular deviation, indicating the ability to accurately detect and comprehend the source location of the icon/earcon.

Plots, comparing the participants' responses and the sound source location (FIGURES 9 – 12), indicate that lower angular deviations were noted when the sound source was located in the front right or left source quadrants. Larger deviations were noted with sound sources located in the quadrants to the rear of the participants' location.

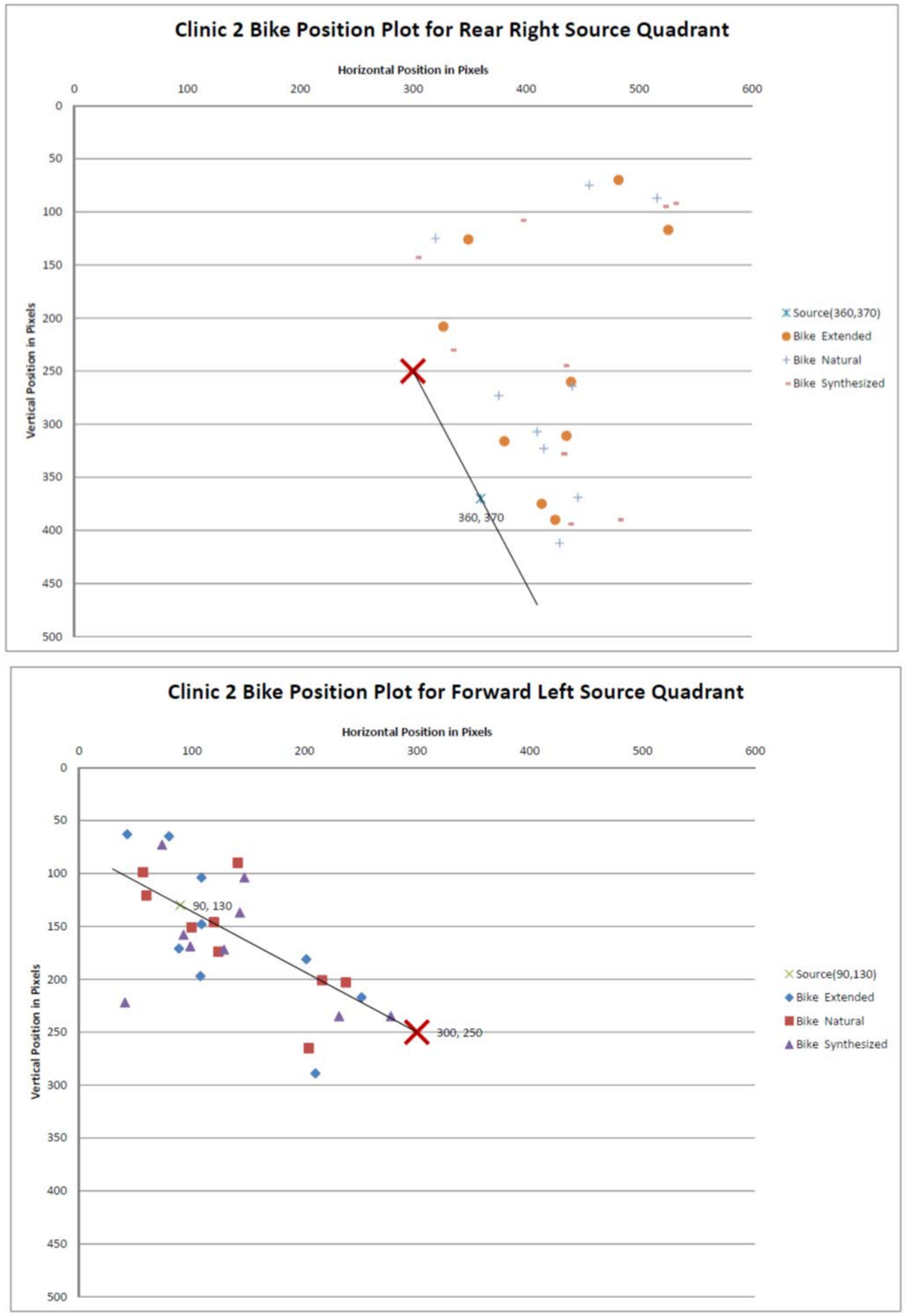


FIGURE 9 Clinic 2 – Bike Location Angular Deviation Results.

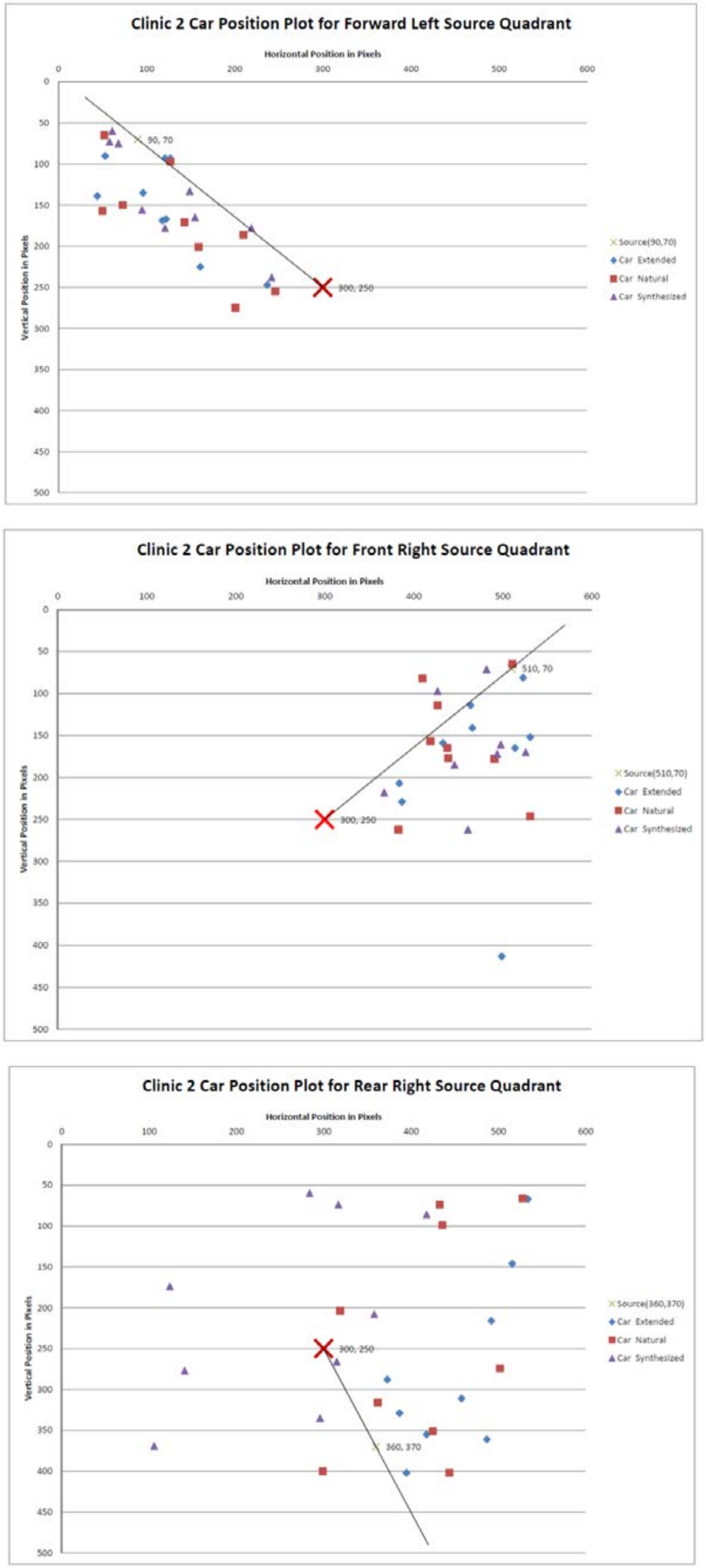
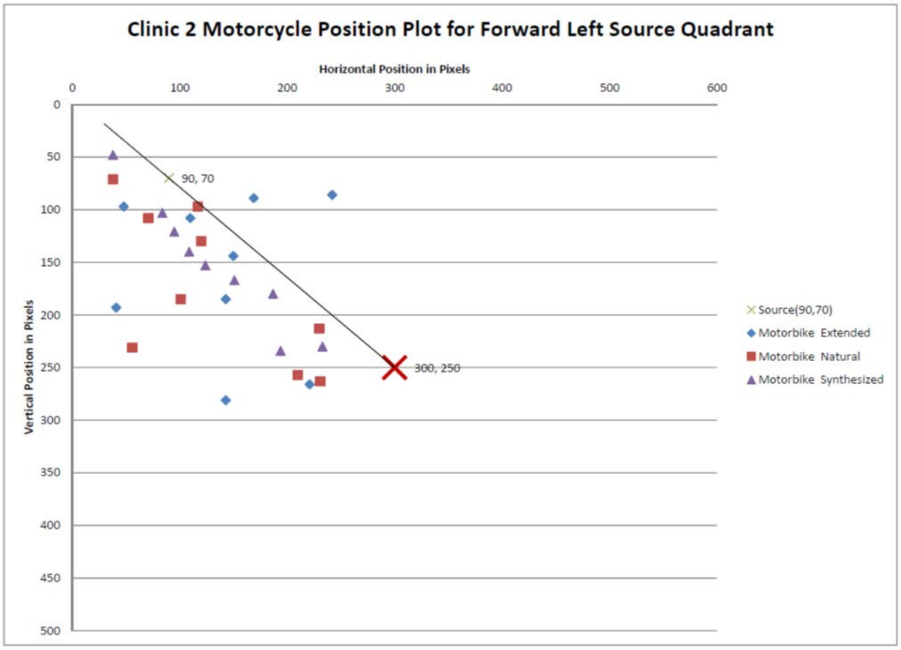


FIGURE 10 Clinic 2 – Car Location Angular Deviation Results.



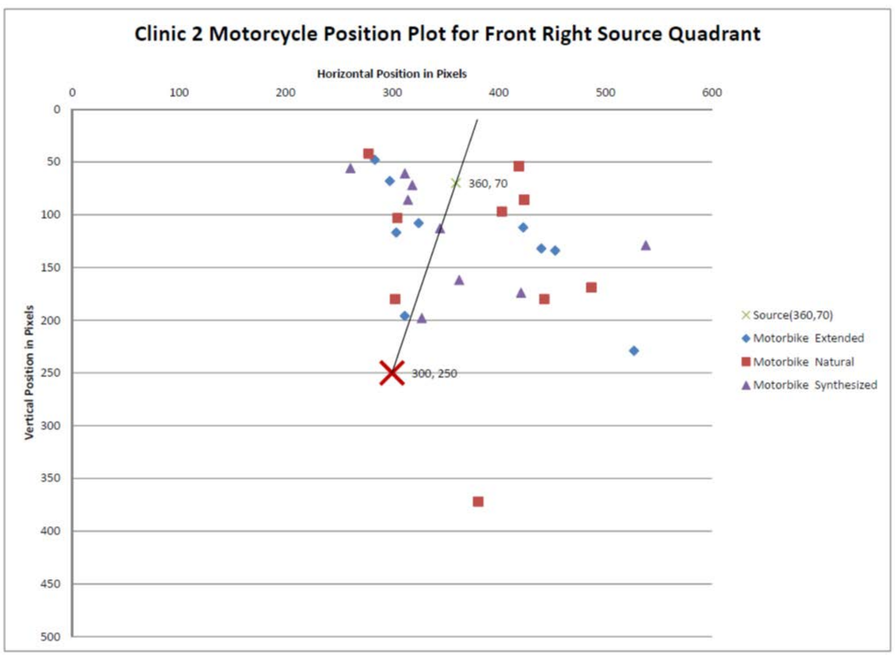
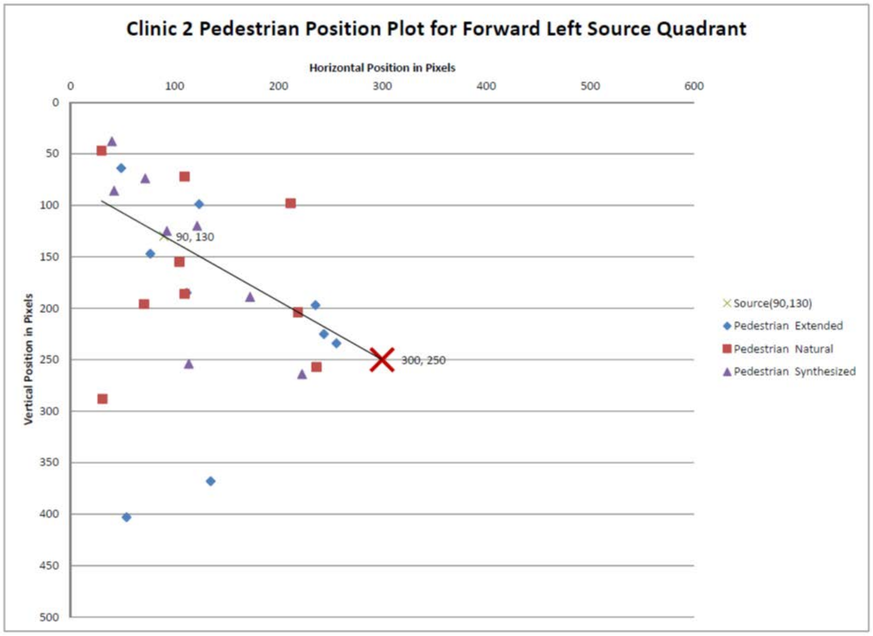


FIGURE 11 Clinic 2 – Motorcycle Location Angular Deviation Results.



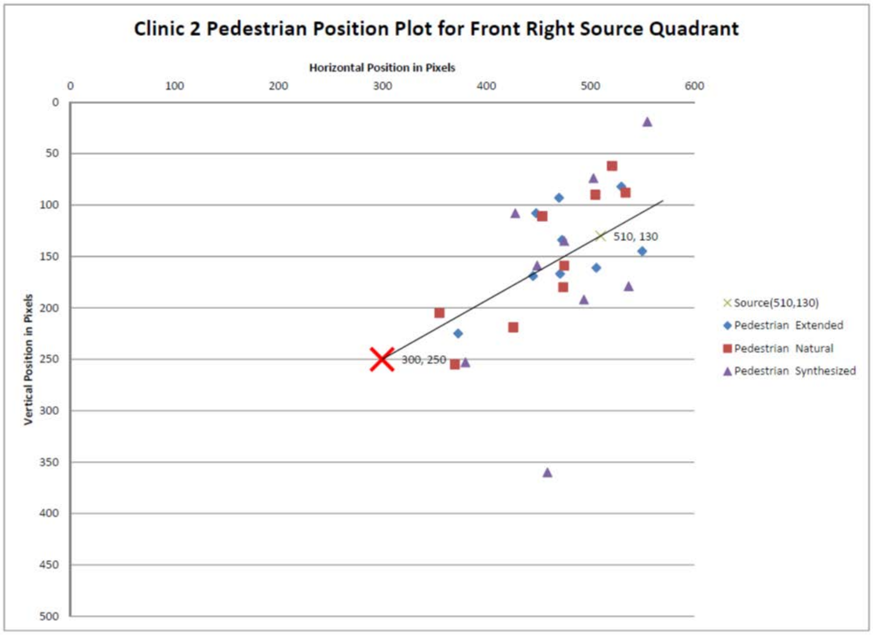


FIGURE 12 Clinic 2 – Pedestrian Location Angular Deviation Results.

4.1.5.3 Clinic 3 Results

Data gathered from clinic 3 was analyzed to assess the direction of movement of the 3D auditory icons/earcons sound source. The analysis focused on the angular deviation between the sound source direction of movement and the participants' indication of the direction of movement. The performance goal is a low angular deviation, indicating the ability to accurately detect and comprehend the direction of movement of the icon/earcon.

In clinic 3, the direction of movement for the sound sources had the same beginning locations as the location in clinic 2. In comparing the angular deviation results from clinic 2 (location) to clinic 3 (beginning direction of movement location), there tended to be lower angular deviations with clinic 3 (FIGURE 13), especially with the natural sounds (icons). The spatial movement, coupled with the context of a traffic scenario, where a safety critical event could occur between truck and road-users, tended to increase the accuracy to assess situational awareness.

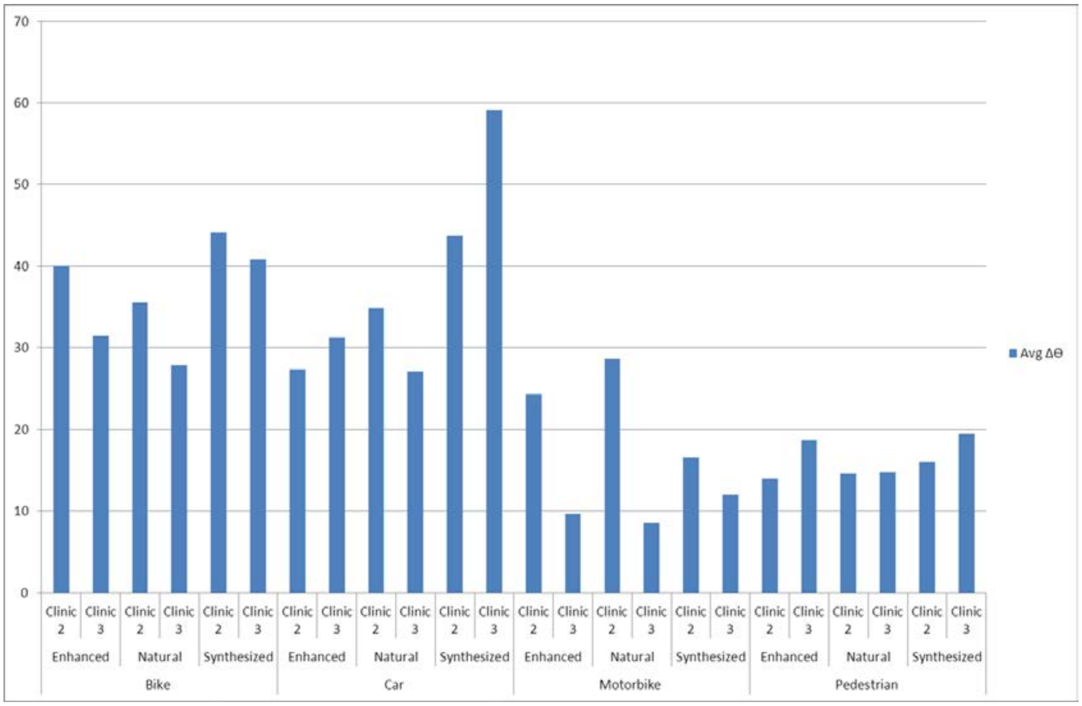


FIGURE 13 Clinic 3 – Angular Deviation Comparison Results.

4.1.6 Conclusions

The results of the test clinics indicated that:

- In analyzing the accuracy of recognizing the 3D auditory icon/earcon (cue recognition), the natural sound theme (icon) and enhanced natural sounds (earcon) tended to have the highest accuracy rates, which indicates a level of intuitiveness and high degree of association to the intended object. However, there was a noticeable decrease in accuracy associated with the synthesized sounds (earcon).
- In comparing the detection of the sound location (cue detection) versus the direction of the movement (cue projection), spatial movement tended to increase the accuracy to assess situational awareness.

After analyzing the aggregate results, it was decided to use the sound themes that were the most accurately recognized in the quickest time to represent the road users in the optimized 3D sound system (FIGURE 14).

Road User	Sound Theme	Accuracy	Mean Response	Std. Deviation
Pedestrian	Enhanced	100 %	1.3 sec	0.9 sec
Bike	Natural	100 %	1.7 sec	1.3 sec
Motorbike	Enhanced	91 %	2.3 sec	2.0 sec
Car	Natural	99 %	2.0 sec	2.0 sec

FIGURE 14 Auditory icons selected for optimized 3D sound system.

4.2 STAGE II

The results from Stage I have demonstrated the potential to effectively use 3D sounds to augment or increase the driver's situational awareness by providing traffic cues, i.e., different simulated traffic situations represented by auditory icons. The evaluation of 3D auditory icons indicated their ability to provide a level of intuitiveness which can lead to increase accuracy in the ability to perceive, comprehend and anticipate. The objective for Stage II of the project was to install the 3D sound system, optimized based on the results in Stage I, into a fully operational truck, and to safely evaluate the effectiveness of the auditory icons during real driving scenarios.

4.2.1 3D Sound Integration into the Truck Cab

The optimized sound system identified in Stage I was integrated into a Class 8 tractor with a sleeper compartment. The vehicle wiring harness was modified to allow overriding of 4 channels of audio input from the stock 6 channel audio system, immediately before the stock amplifier. This was accomplished by means of adding a breakout box that accepts two 3.5mm stereo audio inputs, one for the front channels, and one for the rear channels. The audio outputs from the sound card attached to the test laptop plug directly into the breakout box.

There were four channels available: front left, front right, rear left, and rear right. The front left output from the amplifier was sent to a pair of speakers, one in the dash in front of the driver and the other in the driver side door. The front right output from the amplifier was sent to a pair of speakers, one in the dash in front of the passenger and the other in the passenger side door. The rear channel amplifier outputs were connected to one speaker each in the bunk area, one behind the driver and the other behind the passenger. During the integration set-up activities, it was determined that the location and design of the storage units behind the driver's seat in the cab of the vehicle interfered with the ability to hear the sounds from the rear left speaker in the bunk area. Therefore the speaker was moved to be positioned directly behind the driver seat (FIGURE 15).

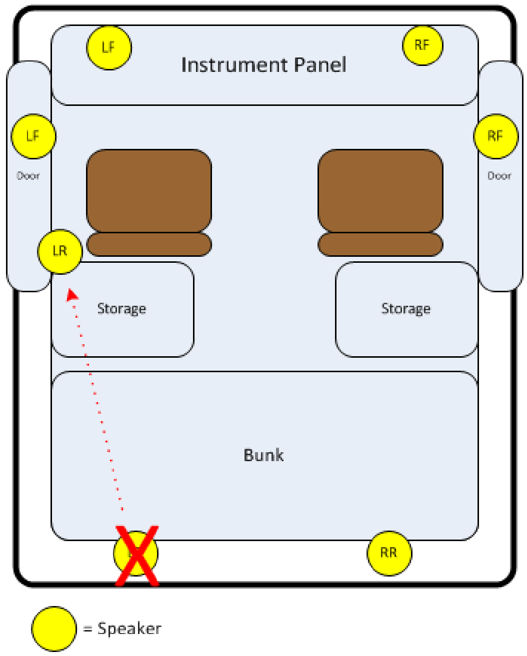


FIGURE 15 Schematic of the speaker placement for the 3D sound integration into the truck cab (plan view).

4.2.2 Driving Clinic Setup

The driving clinic involved an evaluation of the effectiveness of sound icons in a truck cab while conducting actual driving maneuvers. In order to safely evaluate the effectiveness of the auditory icons during real driving scenarios, a test course was designed to simulate a suburban neighborhood delivery scenario where the driver would be turning right and left, and moving forward and backing up into areas representing the driveways of the homes within the neighborhood. The course was marked off in a paved area that was fenced in and away from regular traffic.

4.2.2.1 Course Layout

The layout of the test course was constructed to simulate a suburban neighborhood with two private driveways on each side of a center street (FIGURE 16). C1, C2, and C3 represents segments of the center street in the neighborhood while L1 and L2 represent driveways to homes on the left, and R1 and R2 represent driveways to homes on the right. The area for the course occupied a rectangle roughly 300 feet by 100 feet. The street and driveway corners were denoted by orange traffic cones.

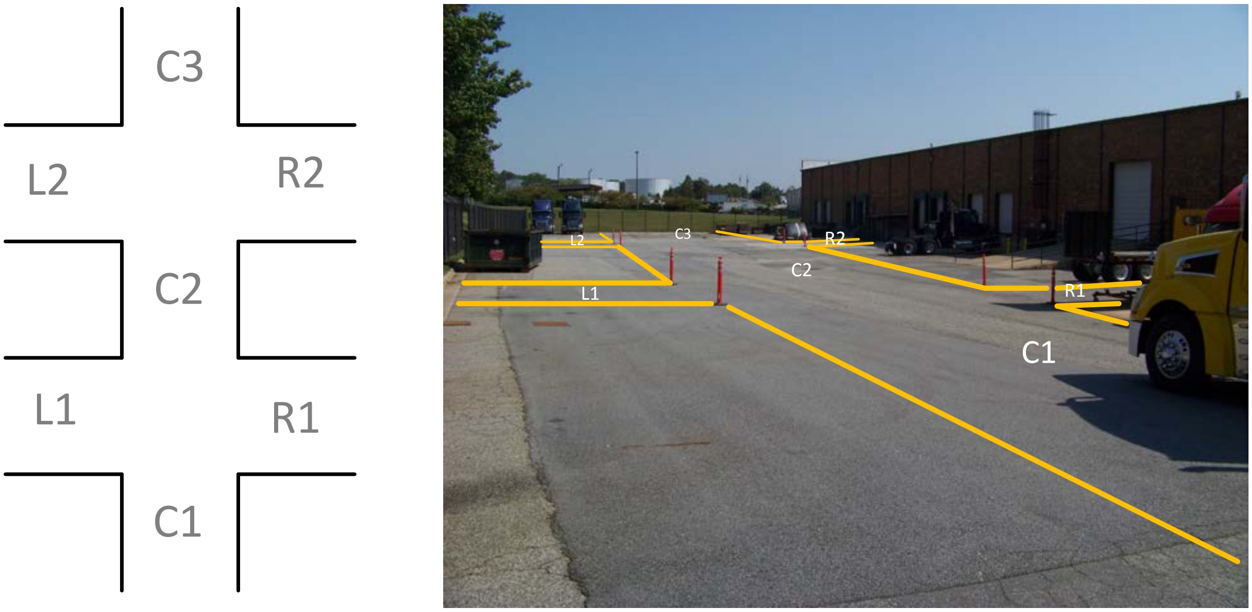


FIGURE 16 Course layout for driving maneuvers.

4.2.2.2 Participants

A total of nine participants were recruited for the study, all of which were males. All had a commercial driver's license (CDL), and were familiar with the driving requirements to operate the Class 8 tractor. Upon their arrival to the test course, the background and purpose of the testing was reviewed with the participants, along with the layout of the course. They were then instructed concerning the details of the equipment setup in the vehicle cab, and instructed how to provide their test responses.

4.2.2.3 Test Procedure

Participants in the test were driving, with a test navigator positioned in the passenger seat, and a test administrator/data collector positioned in the bunk compartment of the vehicle. A laptop PC was connected to the sound system in the truck cab, and was used to generate the sound icons/themes. The participants were directed by the navigator to perform a series of scripted driving maneuvers through the driving course (FIGURE 17).

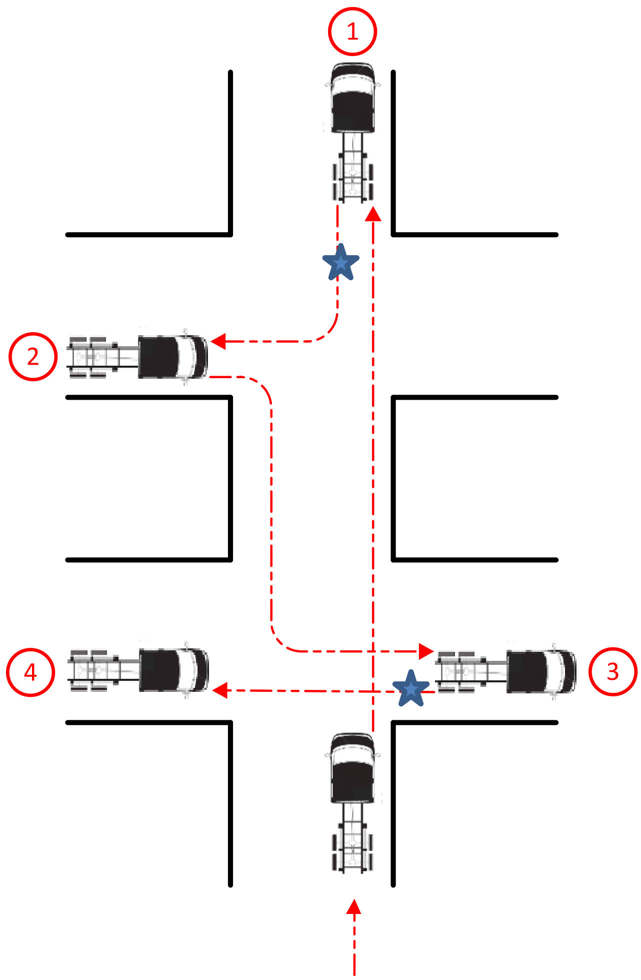


FIGURE 17 Example of one of the graphic representations of the scripted driving maneuvers (blue star indicates when the auditory icon is played during the driving maneuver).

As the driver followed the directions of the navigator, sound icons/themes (based on the findings in Stage 1 – FIGURE 18) were played at predetermined scripted locations. . An indication of the participant's perception of the direction from where the sound originated would have to be by spoken report. Hence the indication of direction was simplified to four quadrants (left front, right front, right rear, and left rear) to avoid ambiguity. Once the sound was played, the driver was asked to operate the vehicle as if it was a real situation, and verbally report what was heard (type of road user) and from what quadrant. After the completion of all of the driving maneuvers, the participants were requested to provide their opinion of the effectiveness of using 3D sounds to increase situational awareness of the driving environment.

Road User	Sound Theme
Pedestrian	Enhanced
Bike	Natural
Motorbike	Enhanced
Car	Natural

FIGURE 18 Auditory icons selected for optimized 3D sound system.

Seated in the bunk area of the cab, the test administrator/data collector was responsible for initiating the audible sounds at the appropriate time, and also recording the feedback from the driver. The survey application (FIGURE 19) was coded to produce the predetermined sounds at the appropriate location that followed along with the scripted test procedure maneuvers. The administrator followed the test script and initiate the sound at the appropriate time, and location in the audible space, by pressing the "Play Sound" button.

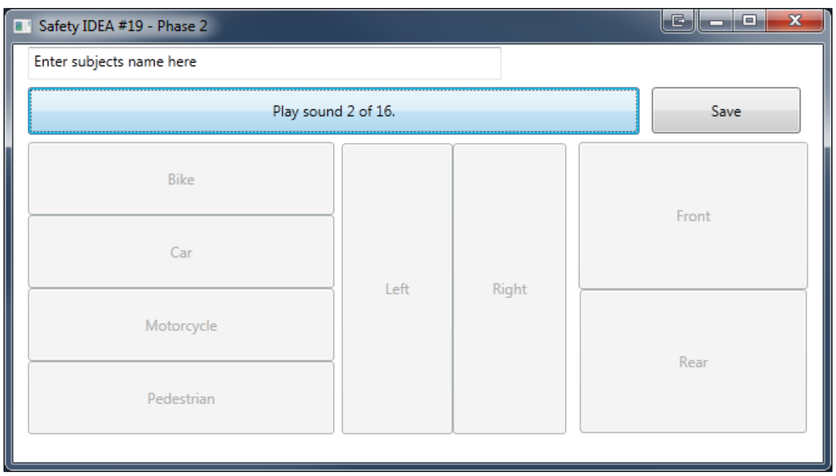


FIGURE 19 The survey application, initiate the sound.

After the sound started playing, the administrator recorded the participants verbal response by indicating the sound type, the hemisphere left or right, and the hemisphere front or back (FIGURE 20). The sound played for 10 seconds, even if the driver responded to the sound before the end of the 10 seconds interval. If the driver failed to identify the sound, or any of the locations, the response of N/A was recorded. If no response is given from the driver within 30 seconds of the sound starting, N/A was automatically recorded, and the next test sound was queued.

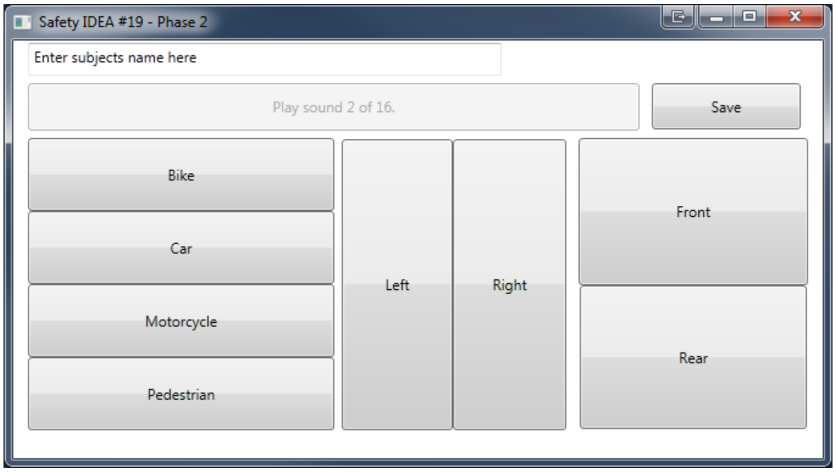


FIGURE 20 The survey application, recording the participant's response.

4.2.3 Results

Data gathered was analyzed to assess the performance in recognizing the 3D auditory icons. The analysis focused on the hit-ratio (percentage of correct selections of the icon in each trial), and the response time. The hit-ratio percentage represents the accuracy of recognition, while the response time indicates length of time required to perceive the icon. The performance goal is high accuracy coupled with a low response time.

In analyzing the accuracy of recognizing the optimized audio icon/earcon, the highest accuracy rates were associated with the bike, motorbike and predestrian, which indicates a level of intuitiveness and high degree of association to the intended object (FIGURE 21). The car had the lowest hit ratio and longest mean response time. It is also noted that recognition of front versus rear was somewhat more accurate than for from left to right. See Matches for pedestrian, bike, and motorbike also in FIGURE 21.

Road User	**Sound Theme**	**Hit Ratio (%)**	**Mean Response Time (secs)**	**Matches Left/Right (%)**	**Matches Front/Rear (%)**
Pedestrian	Enhanced	98	4.2	80.0	100.0
Bike	Natural	100	3.7	88.9	94.4
Motorbike	Enhanced	98	3.3	80.6	97.2
Car	Natural	81	4.6	96.3	96.3

FIGURE 21 Accuracy of icon recognition.

In analyzing the accuracy indicating direction/location of the optimized audio icon/earcon sound source by quadrant (front left; front right; rear left; rear right), sounds from the front quadrants were more accurately recognized, with a lower response time, than sounds from the rear quadrants (FIGURE 22).

Quadrants	**Hit Ratio (%)**	**Mean Response Time (secs)**
Front Left	97	3.2
Front Right	95	3.5
Rear Left	77	3.8
Rear Right	61	5.2

FIGURE 22 Accuracy of direction/location.

When the participants provided their opinion of the effectiveness of using3D sounds to increase situational awareness of the driving environment, comments included (summarized):

- The pedestrian and the bike were the most noticeable, easy to hear sound.
- Any sound used must be distinctly different than any normal sound one hears in the truck. For example, the car sound is not distinctive enough. The car sound tended to blend in with the engine sound of the truck so it was hard to distinguish. Sounds could be louder, needs to be tuned well to the truck.
- The sounds were not annoying or irritiating, so would not turn the system off, but concern about false alarms, and adding the sounds to a vehicle system that already has an increase in alarms (adaptative cruise control, lane depature warnings, etc.).
- The system is beneficial, would be very helpful for blind corners, and especially the rear.
- Verbal word (pedestrian right, motorbike front left) may provide a quicker response than icons. Or maybe provide a visual display cue.

4.2.4 Conclusions

The results of the driving clinic indicated that:

- The highest accuracy rates were associated with the bike, motorbike and predestrian, which indicates a level of intuitiveness and high degree of association to the intended object. The car, although the optimized sound from Stage I, car/natural, had a high hit ratio (100%), the in-vehicle cab ratios were lower (81%). The comments that the engine sound of the truck made the 3D car sound indistinguishable indicates a need to analyze the sound level frequency spectrum of the sounds versus the typical sounds within the cab so that the 3D sounds can be conditioned to be distinguished.
- The sounds from the rear speakers resulted in lower accuracy rates, and slower response times. Previously it was indicated that during the integration set-up activities, it was determined that the location and design of the storage units behind the driver's seat in the cab of the vehicle interfered with the ability to hear the sounds from the rear left speaker in the bunk area. So the speaker was moved to be positioned directly behind the driver seat

(FIGURE 15). This explains the better accuracy and response time for the rear left versus the rear right speaker locations. These results tends to indicate that the existing production speaker arrangement may not be sufficient, and additional and/or a different speaker configuration will be needed which could impact product design and manufacturing costs.

The results of Stage II have demonstrated the potential to effectively use 3D sounds, under realistic driving conditions. All of the participants commented that they felt that this type of system could be beneficial, however their concerns associated with disguishable sounds that are not impacted by other in-vehicle cab sounds, too many alarms/alerts associated with other vehicle systems increasing their annoyance levels, and the possibility of other potential interfaces (vocal/spoken word alert, visual display alert, etc.) indicate areas where further investigation will be needed.

5. PLANS FOR IMPLEMENTATION

The results of the project has shown the utility of using in-vehicle 3D sounds as a technique for augmenting the truck driver's situational awareness. However, it has also identified areas where further investigation will be needed in order to achieve implementation in production vehicles. The research path forward should include:

1. Field operational testing (FOT) to determine the impact of 3D sounds on cognitive workload and driver distraction.
2. Determine if audio icons provide a quicker response than verbal/spoken word (pedestrian right, motorbike front left). The results of Stage II indicated that the audio icons are dependent on having a good sound field, so speaker location is very important. Verbal/spoken word is suspected to have a lower level of speaker location dependence.
3. Development of object detection and recognition systems are needed in order to identify the road users. The 3D sound systems would need to be integrated with advanced safety technologies that provide detection and recognition, in real time, of soft body (pedestrians) and hard body/metallic (bikes, motorcycles, etc.) road users in order to provide the necessary traffic cues to increase SA. This could include camera vision processing systems (FIGURE 23), or also expansion of connected vehicle technologies to include other road users as nodes in the network grid detection and communication system, etc.

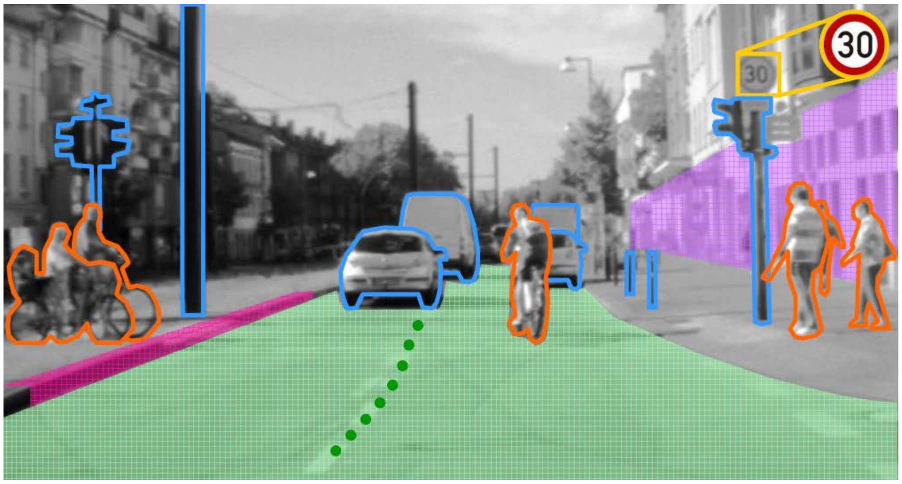


FIGURE 23 Object recognition - Road users detection via camera vision processing systems.

4. Investigation into other possible human machine interfaces may also be necessary in order to reduce the potential of overloading the human's auditory senses (and increase annoyance levels) with too many alarms/alerts associated with other vehicle systems. This could include

development of workload managers that prioritize and regulate when alarms/alerts are initiated for all vehicle subsystems, or use of other sensory modalities (visual display, haptic interfaces, etc.).

6. CONCLUSIONS

The results of this project have demonstrated the potential to effectively use 3D sounds to augment or increase the driver's situational awareness by providing traffic cues, i.e., different simulated traffic situations represented by auditory icons. The evaluation of 3D auditory icons indicated their potential ability to provide an increased level of situational awareness. Further investigation and technological advancements will be needed in order to integrate 3D sounds into production vehicles.

7. INVESTIGATOR PROFILE

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