SAVE-IT

SAfety VEhicles using adaptive Interface Technology (Task 9)

Safety Warning Countermeasures

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9.0 PROGRAM OVERVIEW

Driver distraction is a major contributing factor to automobile crashes. National Highway Traffic Safety Administration (NHTSA) has estimated that approximately 25% of crashes are attributed to driver distraction and inattention (Wang, Knipling, & Goodman, 1996). The issue of driver distraction may become worse in the next few years because more electronic devices (e.g., cell phones, navigation systems, wireless Internet and email devices) are brought into vehicles that can potentially create more distraction. In response to this situation, the John A. Volpe National Transportation Systems Center (VNTSC), in support of NHTSA's Office of Vehicle Safety Research, awarded a contract to Delphi Electronics & Safety to develop, demonstrate, and evaluate the potential safety benefits of adaptive interface technologies that manage the information from various in-vehicle systems based on real-time monitoring of the roadway conditions and the driver's capabilities. The contract, known as SAfety VEhicle(s) using adaptive Interface Technology (SAVE-IT), is designed to mitigate distraction with effective countermeasures and enhance the effectiveness of safety warning systems.

The SAVE-IT program serves several important objectives. Perhaps the most important objective is demonstrating a viable proof of concept that is capable of reducing distraction-related crashes and enhancing the effectiveness of safety warning systems. Program success is dependent on integrated closed-loop principles that, not only include sophisticated telematics, mobile office, entertainment and safety warning systems, but also incorporate the state of the driver. This revolutionary closed-loop vehicle environment will be achieved by measuring the driver's state, assessing the situational threat, prioritizing information presentation, providing adaptive countermeasures to minimize distraction, and optimizing advanced collision warning.

To achieve the objective, Delphi Electronics & Safety has assembled a comprehensive team including researchers and engineers from the University of Iowa, University of Michigan Transportation Research Institute (UMTRI), General Motors, Ford Motor Company, and Seeing Machines, Inc. The SAVE-IT program is divided into two phases shown in Figure i. Phase I spans one year (March 2003--March 2004) and consists of nine human factors tasks (Tasks 1-9) and one technology development task (Task 10) for determination of diagnostic measures of driver distraction and workload, architecture concept development, technology development, and Phase II planning. Each of the Phase I tasks is further divided into two sub-tasks. In the first sub-tasks (Tasks 1, 2A-10A), the literature is reviewed, major findings are summarized, and research needs are identified. In the second sub-tasks (Tasks 1, 2B-10B), experiments will be performed and data will be analyzed to identify diagnostic measures of distraction and workload and determine effective and driver-friendly countermeasures. Phase II will span approximately two years (October 2004--October 2006) and consist of a continuation of seven Phase I tasks (Tasks 2C--8C) and five additional tasks (Tasks 11-15) for algorithm and guideline development, data fusion, integrated countermeasure development, vehicle demonstration, and evaluation of benefits.

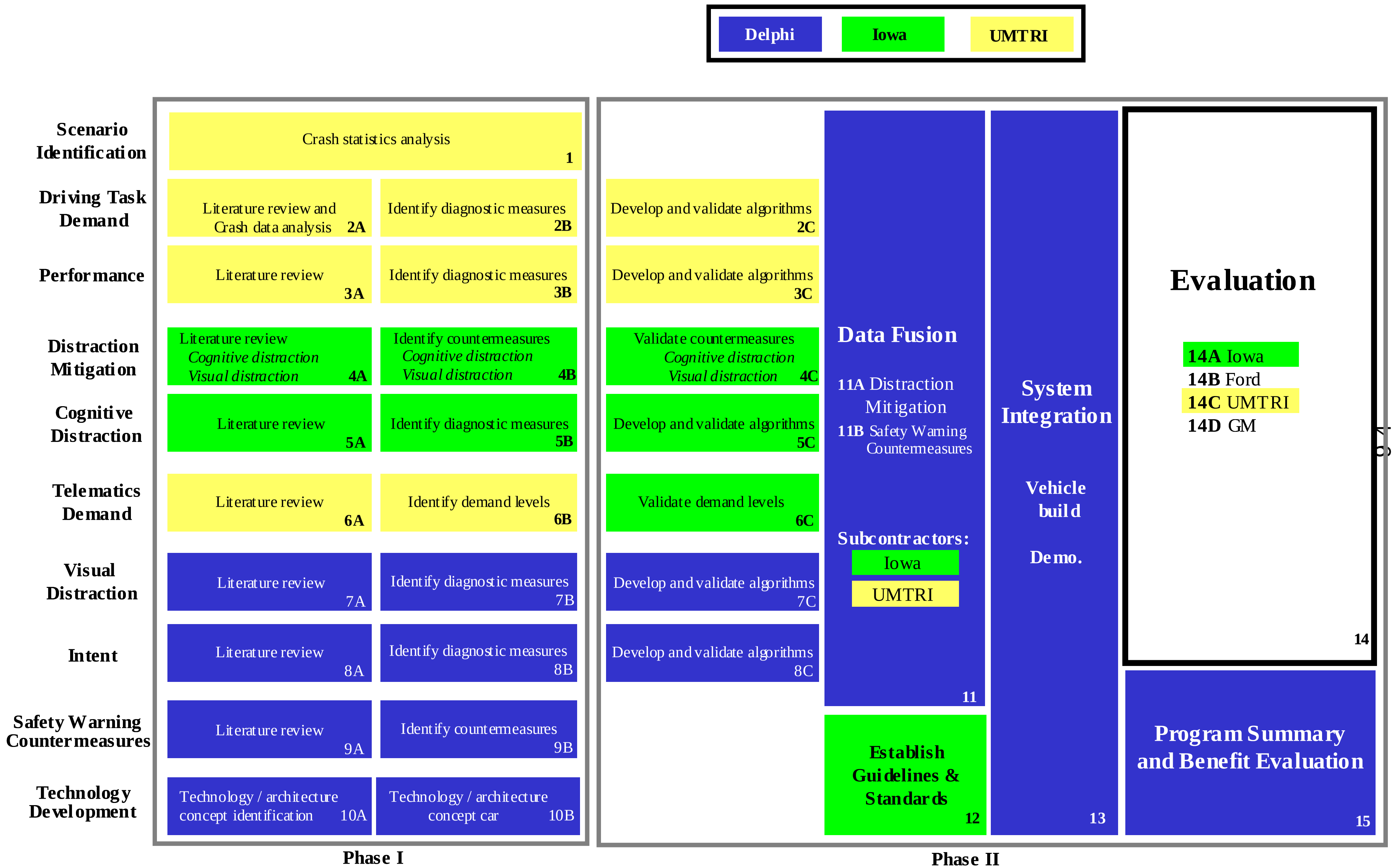

Figure i: SAVE-IT tasks

It is worthwhile to note the SAVE-IT tasks in Figure i are inter-related. They have been chosen to provide necessary human factors data for a two-pronged approach to address the driver distraction and adaptive safety warning countermeasure problems. The first prong (Safety Warning Countermeasures sub-system) uses driver distraction, intent, and driving task demand information to adaptively adjust safety warning systems such as forward collision warning (FCW) systems in order to enhance system effectiveness and user acceptance. Task 1 is designed to determine which safety warning system(s) should be deployed in the SAVE-IT system. Safety warning systems will require the use of warnings about immediate traffic threats without an annoying rate of false alarms and nuisance alerts. Both false alarms and nuisance alerts will be reduced by system intelligence that integrates driver state, intent, and driving task demand information that is obtained from Tasks 2 (Driving Task Demand), 3 (Performance), 5 (Cognitive Distraction), 7 (Visual Distraction), and 8 (Intent).

The safety warning system will adapt to the needs of the driver. When a driver is cognitively and visually attending to the lead vehicle, for example, the warning thresholds can be altered to delay the onset of the FCW alarm or reduce the intrusiveness of the alerting stimuli. When a driver intends to pass a slow-moving lead vehicle and the passing lane is open, the auditory stimulus might be suppressed in order to reduce the alert annoyance of a FCW system. Decreasing the number of false positives may reduce the tendency for drivers to disregard safety system warnings. Task 9 (Safety Warning Countermeasures) will investigate how driver state and intent information can be used to adapt safety warning systems to enhance their effectiveness and user acceptance. Tasks 10 (Technology Development), 11 (Data Fusion), 12 (Establish Guidelines and Standards), 13 (System Integration), 14 (Evaluation), and 15 (Program Summary and Benefit Evaluation) will incorporate the research results gleaned from the other tasks to demonstrate the concept of adaptive safety warning systems and evaluate and document the effectiveness, user acceptance, driver understandability, and benefits and weaknesses of the adaptive systems. It should be pointed out that the SAVE-IT system is a relatively early step in bringing the driver into the loop and therefore, system weaknesses will be evaluated, in addition to the observed benefits.

The second prong of the SAVE-IT program (Distraction Mitigation sub-system) will develop adaptive interface technologies to minimize driver distraction to mitigate against a global increase in risk due to inadequate attention allocation to the driving task. Two examples of the distraction mitigation system include the delivery of a gentle warning and the lockout of certain telematics functions when the driver is more distracted than what the current driving environment allows. A major focus of the SAVE-IT program is the comparison of various mitigation methods in terms of their effectiveness, driver understandability, and user acceptance. It is important that the mitigation system does not introduce additional distraction or driver frustration. Because the lockout method has been shown to be problematic in the aviation domain and will likely cause similar problems for drivers, it should be carefully studied before implementation. If this method is not shown to be beneficial, it will not be implemented.

The distraction mitigation system will process the environmental demand (Task 2: Driving Task Demand), the level of driver distraction [Tasks 3 (Performance), 5 (Cognitive Distraction), 7 (Visual Distraction)], the intent of the driver (Task 8: Intent), and the telematics distraction potential (Task 6: Telematics Demand) to determine which functions should be advised against under a particular circumstance. Non-driving task information and functions will be prioritized based on how crucial the information is at a specific time relative to the level of driving task demand. Task 4 will investigate distraction mitigation strategies and methods that are very well accepted by the users (i.e., with a high level of user acceptance) and understandable to the drivers. Tasks 10 (Technology Development), 11 (Data Fusion), 12 (Establish Guidelines and Standards), 13 (System Integration), 14 (Evaluation), and 15 (Program Summary and Benefit Evaluation) will incorporate the research results gleaned from the other tasks to demonstrate the concept of using adaptive interface technologies in distraction mitigation and evaluate and document the effectiveness, driver understandability, user acceptance, and benefits and potential weaknesses of these technologies.

In particular, driving task demand and driver state (including driver distraction and impairment) form the major dimensions of a driver safety system. It has been argued that crashes are frequently caused by drivers paying insufficient attention when an unexpected event occurs, requiring a novel (non-automatic) response. As displayed in Figure ii, attention to the driving task may be depleted by driver impairment (due to drowsiness, substance use, or a low level of arousal) leading to diminished attentional resources, or allocation to non-driving tasks[1]. Because NHTSA is currently sponsoring other impairment-related studies, the assessment of driver impairment is not included in the SAVE-IT program at the present time. One assumption is that safe driving requires that attention be commensurate with the driving demand or unpredictability of the environment. Low demand situations (e.g., straight country road with no traffic at daytime) may require less attention because the driver can usually predict what will happen in the next few seconds while the driver is attending elsewhere. Conversely, high demand (e.g., multi-lane winding road with erratic traffic) situations may require more attention because during any time attention is diverted away, there is a high probability that a novel response may be required. It is likely that most intuitively drivers take the driving-task demand into account when deciding whether or not to engage in a non-driving task. Although this assumption is likely to be valid in a general sense, a counter argument is that problems may also arise when the situation appears to be relatively benign and drivers overestimate the predictability of the environment. Driving environments that appear to be predictable may therefore leave drivers less prepared to respond when an unexpected threat does arise.

[1] The distinction between driving and non-driving tasks may become blurred sometimes. For example, reading street signs and numbers is necessary for determining the correct course of driving, but may momentarily divert visual attention away from the forward road and degrade a driver's responses to unpredictable danger evolving in the driving path. In the SAVE-IT program, any off-road glances, including those for reading street signs, will be assessed in terms of visual distraction and the information about distraction will be fed into adaptive safety warning countermeasures and distraction mitigation sub-systems.

A safety system that mitigates the use of in-vehicle information and entertainment system (telematics) must balance both attention allocated to the driving task that will be assessed in Tasks 3 (Performance), 5 (Cognitive Distraction), and 7 (Visual Distraction) and attention demanded by the environment that will be assessed in Task 2 (Driving Task Demand). The goal of the distraction mitigation system should be to keep the level of attention allocated to the driving task above the attentional requirements demanded by the current driving environment. For example, as shown in Figure ii, "routine" driving may suffice during low or moderate driving task demand, slightly distracted driving may be adequate during low driving task demand, but high driving task demand requires attentive driving.

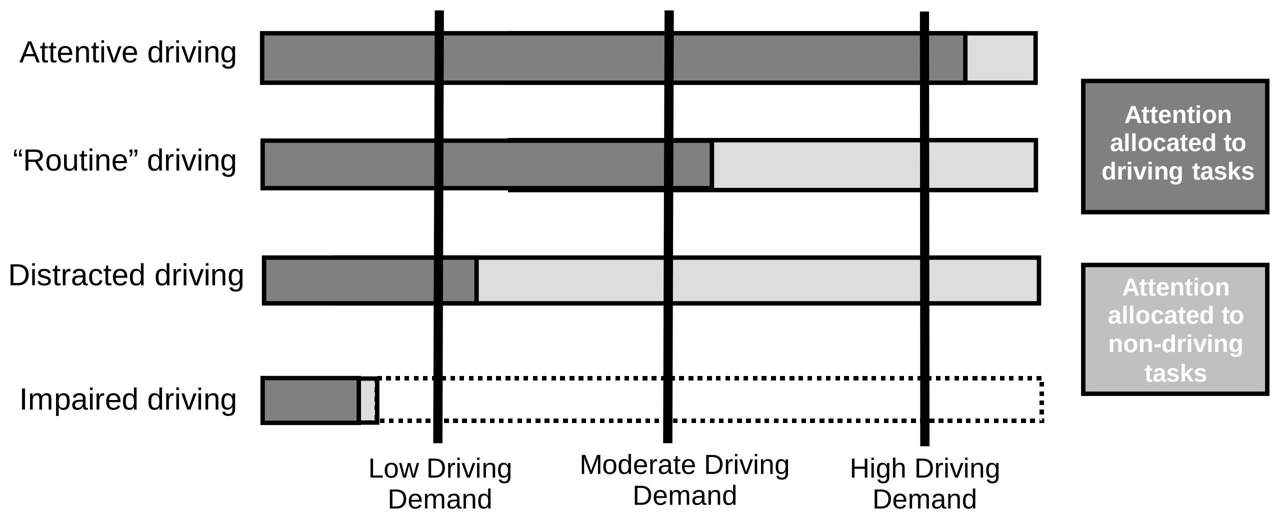

Figure ii. Attention allocation to driving and non-driving tasks

It is important to note that the SAVE-IT system addresses both high-demand and low-demand situations. With respect to the first prong (Safety Warning Countermeasures sub-system), the safety warning systems (e.g., the FCW system) will always be active, regardless of the demand. Sensors will always be assessing the driving environment and driver state. If traffic threats are detected, warnings will be issued that are commensurate with the real time attentiveness of the driver, even under low-demand situations. With respect to the second prong (Distraction Mitigation sub-system), driver state including driver distraction and intent will be continuously assessed under all circumstances. Warnings may be issued and telematics functions may be screened out under both high-demand and low-demand situations, although the threshold for distraction mitigation may be different for these situations.

It should be pointed out that drivers tend to adapt their driving, including distraction behavior and maintenance of speed and headway, based on driving (e.g., traffic and weather) and non-driving conditions (e.g., availability of telematics services), either consciously or unconsciously. For example, drivers may shed non-driving tasks (e.g., ending a cell phone conversation) when driving under unfavorable traffic and weather conditions. It is critical to understand this "driver adaptation" phenomenon. In principle, the "system adaptation" in the SAVE-IT program (i.e., adaptive safety warning countermeasures and adaptive distraction mitigation sub-systems) should be carefully implemented to ensure a fit between the two types of adaptation: "system adaptation" and "driver adaptation". One potential problem in a system that is inappropriately implemented is that the system and the driver may be reacting to each other in an unstable manner. If the system adaptation is on a shorter time scale than the driver adaptation, the driver may become confused and frustrated. Therefore, it is important to take the time scale into account. System adaptation should fit the driver's mental model in order to ensure driver understandability and user acceptance. Because of individual difference, it may also be important to tailor the system to individual drivers in order to maximize driver understandability and user acceptance. Due to resource constraints, however, a nominal driver model will be adopted in the initial SAVE-IT system. Driver profiling, machine learning of driver behavior, individual difference-based system tailoring may be investigated in future research programs.

Communication and Commonalities Among Tasks and Sites

In the SAVE-IT program, a "divide-and-conquer" approach has been taken. The program is first divided into different tasks so that a particular research question can be studied in a particular task. The research findings from the various tasks are then brought together to enable us to develop and evaluate integrated systems. Therefore, a sensible balance of commonality and diversity is crucial to the program success. Diversity is reflected by the fact that every task is designed to address a unique question to achieve a particular objective. As a matter of fact, no tasks are redundant or unnecessary. Diversity is clearly demonstrated in the respective task reports. Also documented in the task reports is the creativity of different task owners in attacking different research problems.

Task commonality is very important to the integration of the research results from the various tasks into a coherent system and is reflected in terms of the common methods across the various tasks. Because of the large number of tasks (a total of 15 tasks depicted in Figure i) and the participation of multiple sites (Delphi Electronics & Safety, University of Iowa, UMTRI, Ford Motor Company, and General Motors), close coordination and commonality among the tasks and sites are key to program success. Coordination mechanisms, task and site commonalities have been built into the program and are reinforced with the bi-weekly teleconference meetings and regular email and telephone communications. It should be pointed out that little time was wasted in meetings. Indeed, some bi-weekly meetings were brief when decisions can be made quickly, or canceled when issues can be resolved before the meetings. The level of coordination and commonality among multiple sites and tasks is un-precedented and has greatly contributed to program success. A selection of commonalities is described below.

Commonalities Among Driving Simulators and Eye Tracking Systems In Phase I
Although the Phase I tasks are performed at three sites (Delphi Electronics & Safety, University of Iowa, and UMTRI), the same driving simulator software, Drive Safety™ (formerly called GlobalSim™) from Drive Safety Inc., and the same eye tracking system, FaceLab™ from Seeing Machines, Inc. are used in Phase I tasks at all sites. The performance variables (e.g., steering angle, lane position, headway) and eye gaze measures (e.g., gaze coordinate) are defined in the same manner across tasks.

Common Dependent Variables An important activity of the driving task is tactical maneuvering such as speed and lane choice, navigation, and hazard monitoring. A key component of tactical maneuvering is responding to unpredictable and probabilistic events (e.g., lead vehicle braking, vehicles cutting in front) in a timely fashion. Timely responses are critical for collision avoidance. If a driver is distracted, attention is diverted from tactical maneuvering and vehicle control, and consequently, reaction time (RT) to probabilistic events increases. Because of the tight coupling between reaction time and attention allocation, RT is a useful metric for operationally defining the concept of driver distraction. Furthermore, brake RT can be readily measured in a driving simulator and is widely used as input to algorithms, such as the forward collision warning algorithm (Task 9: Safety Warning Countermeasures). In other words, RT is directly related to driver safety. Because of these reasons, RT to probabilistic events is chosen as a primary, “ground-truth” dependent variable in Tasks 2 (Driving Task Demand), 5 (Cognitive Distraction), 6 (Telematics Demand), 7 (Visual Distraction), and 9 (Safety Warning Countermeasures).

Because RT may not account for all of the variance in driver behavior, other measures such as steering entropy (Boer, 2001), headway, lane position and variance (e.g., standard deviation of lane position or SDLP), lane departures, and eye glance behavior (e.g., glance duration and frequency) are also be considered. Together these measures will provide a comprehensive picture about driver distraction, demand, and workload.

Common Driving Scenarios For the tasks that measure the brake RT, the "lead vehicle following" scenario is used. Because human factors and psychological research has indicated that RT may be influenced by many factors (e.g., headway), care has been taken to ensure a certain level of uniformity across different tasks. For instance, a common lead vehicle (a white passenger car) was used. The lead vehicle may brake infrequently (no more than 1 braking per minute) and at an unpredictable moment. The vehicle braking was non-imminent in all experiments (e.g., a low value of deceleration), except in Task 9 (Safety Warning Countermeasures) that requires an imminent braking. In addition, the lead vehicle speed and the time headway between the lead vehicle and the host vehicle are commonized across tasks to a large extent.

Subject Demographics It has been shown in the past that driver ages influence driving performance, user acceptance, and driver understandability. Because the age effect is not the focus of the SAVE-IT program, it is not possible to include all driver ages in every task with the budgetary and resource constraints. Rather than using different subject ages in different tasks, however, driver ages are commonized across tasks. Three age groups are defined: younger group (18-25 years old), middle group (35-55 years old), and older group (65-75 years old). Because not all age groups can be used in all tasks, one age group (the middle group) is chosen as the common age group that is used in every task. One reason for this choice is that drivers of 35-55 years old are the likely initial buyers and users of vehicles with advanced technologies such as the SAVE-IT systems. Although the age effect is not the focus of the program, it is examined in some tasks. In those tasks, multiple age groups were used.

The number of subjects per condition per task is based on the particular experimental design and condition, the effect size shown in the literature, and resource constraints. In order to ensure a reasonable level of uniformity across tasks and confidence in the research results, a minimum of eight subjects is used for each and every condition. The typical number of subjects is considerably larger than the minimum, frequently between 10-20.

Other Commonalities   In addition to the commonalities across all tasks and all sites, there are additional common features between two or three tasks. For example, the simulator roadway environment and scripting events (e.g., the TCL scripts used in the driving simulator for the headway control and braking event onset) may be shared between experiments, the same distraction (non-driving) tasks may be used in different experiments, and the same research methods and models (e.g., Hidden Markov Model) may be deployed in various tasks. These commonalities afford the consistency among the tasks that is needed to develop and demonstrate a coherent SAVE-IT system.

The Content and Structure of the Report

The report submitted herein is a final report for Task 9 (Safety Warning Countermeasures) that documents the research progress to date (March 2003-March 2004) in Phase I. In this report, the major results from the literature review are summarized to determine the research needs for the present study, the experimental methods and resultant data are described, diagnostic measures and preliminary algorithms are identified, and human factors recommendations are offered.

9.1 INTRODUCTION

The objective of Task 9 (Safety Warning Countermeasures) is to improve safety warning systems by designing these systems to adaptively respond to workload, distraction, and demand information. These systems will adaptively modify safety-warning countermeasures, such as forward collision warning (FCW) or lane drift warning (LDW) to the instantaneous attention allocation of the driver that is assessed in Tasks 3 (Performance), 5 (Cognitive Distraction), 7 (Visual Distraction), and 8 (Intent). For example, if a driver is highly attentive to the forward-visual scene and is not cognitively distracted, an FCW alert could either be delayed or suppressed completely. Conversely, if a driver is highly distracted and not attending to the forward-visual scene, an FCW alert could be initiated much earlier or the driver could be notified if the lead vehicle suddenly begins decelerating. Adaptive enhancements to safety warning countermeasures will serve the dual goals of reducing nuisance alerts and providing earlier warnings when the driver needs it most. Whereas in non-adaptive systems, there is a tradeoff between earlier warnings and the number of nuisance alerts, adaptive systems offer the possibility of achieving both goals simultaneously. Adaptive systems may potentially adapt to provide less annoying or less frequent warnings when drivers are attentive and more capable of responding without the aid of the warning system without sacrificing safety. When drivers do appear to require the assistance of warning systems (such as when they are distracted), the warnings may be presented either earlier or in a more salient manner. Early feedback from the ACAS FOT program suggests that some drivers were intolerant of warnings that occurred when they were attentive, claiming that the warnings were not necessary. Because Task 9 studies the methods of adaptive enhancements, it is critical to the "Safety Warning Countermeasure" sub-system in the SAVE-IT program.

During the early stages of this task a set of countermeasures was identified for further analysis in the SAVE-IT program. Non-adaptive versions of these countermeasures were developed prior to an evaluation of how these countermeasures can be enhanced using adaptive interface technology. The end product of this task will be a set of adaptive and non-adaptive safety warning countermeasures to be implemented in the evaluation phase of the SAVE-IT program. These countermeasures will be developed further in Task 11B (Data Fusion: Safety Warning Countermeasures) before the System Integration and final Evaluation.

Task 9A (Literature review of Safety Warning Countermeasures) reviewed the literature and summarized the major findings in the Task 9A literature review report. Similar to Task 1 (Scenario Identification) literature review report, Task 9A report briefly reviews the crash statistics to reveal which safety warning systems are the most appropriate focus of the SAVE-IT program. Based on the crash statistics and the development of countermeasure technology, the following four countermeasure systems were proposed for potential application.

1. Forward Collision Warning (FCW)
2. Lane Drift Warning (LDW)
3. Stop Sign Violation Warning (SSVW)

4. Blind Spot Warning (BSW)

The Task 9A literature review report focused primarily on FCW, due to the fact that rear-end collisions are the most prevalent type of accident on United States roadways, the apparent direct link between rear-end collisions and driver distraction, and because the ACAS FOT program is demonstrating the challenges of nuisance alerts in FCW systems. The report described several algorithm alternatives, including algorithms based on the criteria of time-headway, time-to-contact, and the underlying kinematic constraints (i.e., the potential of the host vehicle to decelerate). Because the latter category of algorithm considers both reaction time and the capacity of the host vehicle to decelerate, it offers a more comprehensive model than the other two categories. Burgett, Carter, Miller, Najm, and Smith (1998) proposed one of the first versions of this algorithm, and the Collision Avoidance Metrics Partnership (CAMP) developed a collision avoidance algorithm using required deceleration as a criterion for forward collision warning. Reaction time is likely to vary considerably across parameters such as the timing of the warning system, the type of threat event (e.g., lead vehicle braking compared with lead vehicle stopped), and perhaps most of all, the level of attentiveness of the driver. For greatly distracted drivers, it is reasonable to expect brake reaction times approaching 2.5 s, however, for drivers who are highly attentive or expecting an incident, much shorter brake reaction times (in the order of 1 s) are likely. Ideally the system could detect the state of the driver (e.g., distracted/non-distracted and drowsy/alert) and adapt the reaction time accordingly. The question of whether to include a cautionary alert level in an FCW system was discussed. It was argued that because cautionary alerts provide the driver with an opportunity to experience the alert behaving appropriately in a less annoying form (no auditory), they are likely to build driver confidence in the system.

Task 9A report also investigated the application of adaptive enhancements to LDW systems. Although the types of accidents that LDW systems are designed to prevent are not as common as rear-end accidents, they are quite dangerous, and account for a disproportionate number of fatalities. Several versions of lane drift algorithms are examined and a first-order (speed-based) algorithm using time-to-line-crossing (TLC) may be preferred. Prior research on the driver vehicle interface for LDW systems provides conflicting accounts of what constitutes the ideal interface. Although haptic warning stimuli appear to show promise, there may be risks associated with implementing haptic feedback through the steering wheel. On the other hand, auditory stimuli may present difficulties resulting from excessive annoyance. Due to the complexity of driving in the real world and because lane-keeping performance requirements vary greatly across roadways and circumstances, non-adaptive LDW systems have the potential to overwhelm the driver with nuisance alerts. It was argued that information about driver state may be useful for reducing an otherwise potentially large number of nuisance alerts.

Intersection accidents are another important category of accidents and roadway fatalities in the United States, however, the large variability in the different types of intersection accidents may demand that the intersection accident category be broken into several smaller sub-categories. Many of these intersection accident sub-categories would require knowledge of the phase of the traffic signal and a large sensor-coverage area. These requirements suggest that the countermeasures for many types of intersection accidents require infrastructure support. This requirement places many of the types of intersection accidents beyond the scope of this task, which focuses on vehicle-based warning systems. One type of countermeasure that does not require a wide sensor field-of-view or infrastructure support has been referred to as a Stop Sign Violation Warning (SSVW) system. This system can warn the driver when the threat of stop sign violation has detected.

Although lane-change/merge accidents are less prevalent and appear to lead to fewer fatalities on United States roadways, Blind Spot Warning (BSW) systems are beginning to emerge on the market and there is a clear and direct link between BSW systems and driver intention. The task 9A report suggested that a visual-only display be used to indicate the presence of an object in the blind spot and auditory stimuli be reserved only for imminent alerts, when the turn signal is activated or some other indication is present that the driver intends to change lanes.

Following the review of major results, the Task 9A report presented some preliminary concepts concerning how these safety warning countermeasure systems can be adapted to driver state information. For example, the alert criteria may be adjusted based on the information of driver state to alter the timing of warnings. A more extreme option would be suppressing FCW alerts completely when the driver is attentive. Prior to the SAVE-IT program, there has been relatively little published research comparing different methods for adapting Safety Warning Countermeasures. The implementation and comparison of adaptation methods was the focus of the Experiments in Task 9B.

9.2 EXPERIMENT 1 METHOD

The primary objective of Experiment 1 was to determine the relationship between the Brake Reaction Time (BRT) results emerging from the other SAVE-IT tasks and the BRT that can be expected in an FCW alerting situation. Many warning algorithms use an estimate of the driver's BRT to determine the most effective moment to issue a warning to the driver. For example, a driver who is expected to take 2 s to respond to an alert should be warned 1 s earlier than a driver who is expected to take 1 s to respond. The predicted BRT to an alert is therefore an important input into an algorithm for issuing an alert at the most appropriate moment.

There is an important distinction between the BRT requirements of a warning algorithm and the BRT that was measured in the other SAVE-IT tasks (Task 5: Cognitive Distraction and Task 7: Visual Distraction). Warning algorithms predict the driver's reaction time to an alert (e.g., FCW alert tone) rather than their reaction time to the event (e.g., lead vehicle braking). Because an alert may occur some period of time after the onset of the event, the reaction time to an alert will usually be shorter than the reaction time to the event. In the other SAVE-IT tasks the driver was not warned and BRT was defined as the time between the lead vehicle braking event and the time that the driver began to depress the brake pedal. For the purposes of this experiment, *Alerted BRT* is defined as the time between the FCW alert activation and the time the driver first begins to depress the brake pedal.

The inclusion of an FCW alert to the BRT study also requires that a more threatening event be used. Tasks 5 (Cognitive Distraction) and 7 (Visual Distraction) employed a relatively mild event, wherein the lead vehicle began braking at a rate of -2 to -3 m/s^2 at a time-headway of 1.8 s. The difficulty of these relatively mild braking stimuli for this experiment is that in many cases the driver is likely react to the event before the FCW alert is even issued. Such a methodology could lead to negative Alerted BRT values that would be unrealistic for predicting the driver's behavior in more threatening circumstances. FCW systems must assume that the alert provides information to the driver to which the driver does not otherwise have access. In order to better understand the correspondence between the BRT measures of Tasks 5 and 7 (Cognitive and Visual Distraction) and the Alerted BRT requirements of a warning algorithm, Experiment 1 replicated some of the distraction conditions from these tasks and measured the Alerted BRT to a more threatening braking event (-5 m/s^2).

9.2.1 Participants

Thirty-six participants, between the ages of 35 and 52 were recruited from Delphi in Kokomo, IN. Participants were assigned to the three experimental groups (non-distraction, visual distraction, and cognitive distraction) based on age and gender. Each group contained six males and six females and had an average age of 43. The standard deviation for the age of the three groups ranged from 4.6 (non-distraction and cognitive distraction) to 6.1 (visual distraction). Because a disproportionate number of Delphi employees that are based in Kokomo are engineers, participants who are engineers were distributed evenly across groups and participants were screened to ensure that no more than one-quarter of each group was made up of engineers. The non-engineering population included employees who served Delphi Corporation in financial, secretarial, managerial, and human resources roles.

9.2.2 Apparatus

The Delphi Driving Simulator is a fixed-base Drive-Safety simulator (see Figure 9.1). The simulator projected a 1024x768-pixel 50-deg-vertical forward field-of-view image located at the front bumper of the vehicle cab. The vehicle handling system was configured to represent a mid-size front wheel drive sedan, such as a Ford Taurus. Steering feedback was presented with a force-feedback torque motor, to reproduce the feel of the road at the steering wheel, as well as the forces on the front tires during evasive maneuvers. The vehicle cab consists of the front half of a 1995 Pontiac Bonneville exterior (with doors and roof removed), with a 1996 Buick Park Avenue instrument cluster and dashboard. The cab was equipped with a full-color reconfigurable 2.5x3-deg of visual angle HUD, driven by 230x263-pixel 1.3-inch-diagonal cell, which was used for this experiment to display speed and alert-level. The HUD image was projected at the front bumper of the vehicle, displaying graphics that were generated using Altia software, and the supporting PC platform was linked to the simulator through a local ethernet network. The HUD brightness was preset to an appropriate level for the lighting conditions of the simulator room, and was not adjustable by the participant. Speakers were placed in the engine compartment of the cab directly in front of the driver and the volume was set to play the alert tone at 72 dBA.

Figure 9.1. Photograph of the Delphi Driving Simulator.

The FCW system used a kinematic-constraints algorithm (see Task 9 Literature Review) to provide an imminent warning 1.5 s before the last moment that the driver could brake (assuming a driver braking response of -5 m/s^2) in order to avoid colliding with the lead vehicle. Whereas the cautionary collision warning was triggered immediately after the braking event, participants received the imminent collision warning on average 690 ms after the lead vehicle began braking at -5 m/s^2. The time between the braking event and the imminent alert varied between 400 and 900 ms, with a standard deviation of 107 ms. The variation in timing was largely due to the variation in the host and lead vehicle speeds at the moment the lead vehicle began braking. The logic of the FCW visual interface is displayed in Figure 9.2. A half-second tone using a double sequence of 2500-Hz and 2650-Hz pulses was used for the auditory warning stimulus for the imminent warning. No auditory stimulus was presented in association with the cautionary warning phase.

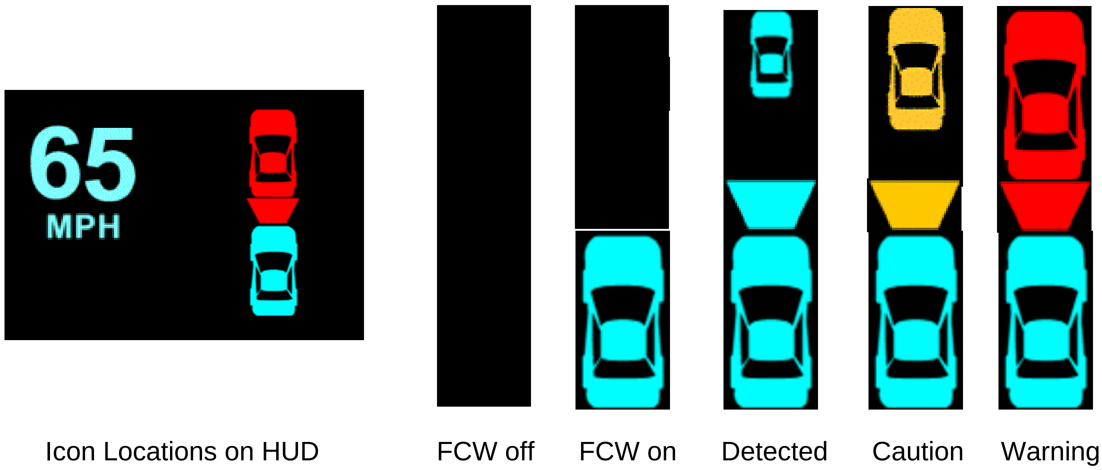

Figure 9.2. HUD icon graphics. The left display indicates where the FCW icons were presented in relation to the speedometer display. The right displays indicate the FCW icons for representing the different FCW system states. The FCW system was activated when the host vehicle reached 25 mph. Note that black appears transparent on a HUD.

Eye glance variables were measured and recorded with the faceLab eye tracking system developed by Seeing Machines, Inc. (Heinzmann & Zelinsky, 1998; Victor, Blomberg, & Zelinsky, 2001). The FaceLab system consisted of a stereo head with two Sony cameras for image capturing, and a Dell computer for image processing and gaze coordinate determination. The stereo head was installed above the dashboard. The simulator room was dimly illuminated to minimize glares and reflections. A 9 x 4 infrared LED array. It used the "image processing using template matching feature tracking" method to track both the head and eye movements. An initial calibration was required to mark the salient facial features such as the eye corners and mouth corners. Once calibrated, the system operated automatically without subjects' intervention. It generated output measures such as head position and orientation, eye gaze coordinates (e.g., pitch and yaw), eye closures, and associated confidence levels.

9.2.3 Design

This experiment used a single-factor between-subjects experimental design to examine the effects of distraction on Alerted BRT. Twelve participants were assigned to each of the following three groups:

1. ***Control*** – Participants were provided with no explicit distraction during the experiment.
2. ***Visual Distraction*** – Participants were provided with a visual distraction task that was identical to one of the distraction conditions used in Task 7 (Visual Distraction).
3. ***Cognitive Distraction*** – Participants were provided with a cognitive distraction task that was identical to one of the distraction conditions used in Task 5 (Cognitive Distraction).

The primary dependent variable for this experiment was Alerted BRT, defined as the time interval between the onset of the imminent FCW alert and the moment that the driver first depresses the brake pedal.

To examine the effects of driver expectation on the Alerted BRT, a repetition of the braking event was presented to the control group. The control-group participants were instructed to expect a similar braking event during this repetition (Drive 3) that they had just experienced on the last (surprise) drive (Drive 2). This condition was referred to as the ***High-Expectancy*** condition.

9.2.4 Procedure

After completing the informed consent forms, participants were told "the purpose of this experiment will be to investigate how safety warnings may be designed to take the driver's state of distraction into account" (the actual purpose of Experiment 2). The eye-tracking system was calibrated to their features and the HUD was adjusted to the appropriate angle. Following the HUD adjustment, participants were informed that the HUD would display their speed on the left and the status of the warning systems on the right. Participants were not instructed on the precise nature of the warning systems. Instead, they were then instructed that

> *the first two blocks will be practice blocks and will last about 5 minutes each. After that, you will begin experiencing the safety warnings and will be asked to answer some questions regarding your opinions about the warnings after each drive.*
> *The purpose of this first block is for you to get accustomed to driving at 65 mph in the driving simulator. The scene will start with you parked behind a lead vehicle. When you are ready, put the vehicle in Drive and the lead vehicle will begin moving. Accelerate behind the lead vehicle until you reach a speed of 65 mph. As you follow the lead vehicle, try to maintain a speed of as close to 65 mph as possible. You are never to pass the lead vehicle at any time during any of the drives. After 5 minutes the drive will automatically end.*

The instructions were designed to surprise the participants with the lead-vehicle braking event and effectively remove any expectations that participants might bring with them to the driving simulator that the lead vehicle would abruptly brake during the first and second drives. Whereas it was true that the first drive would be practice and would last for about 5 minutes, the second drive was designed to gather data on the Alerted BRT and would only last approximately half as long. After the completion of the first drive, participants were informed that the next drive would be the same except if they were in one of the distraction conditions, they were informed that they would now practice the secondary task. The participants in the distraction conditions were then instructed on how to perform the secondary tasks.

The Visual-distraction task was the simple reading task used in the Task 7 (Visual Distraction) experiment, in which participants were asked to read aloud a page of words. In order to control the level of visual distraction, unrelated words were used. The words were written in sans serif font with mixed upper and lower case letters. They extended a visual angle of 22’ for upper cases and 17’ for lower cases. They were presented in white and displayed in three rows of three words on a black background. A wide separation existed between the rows to encourage chunking on a row-by-row basis. The words were displayed on a monitor in the center-stack region (33° horizontal and 28° downward). Participants were instructed to begin reading whenever they heard a single beep and saw the words appear on the monitor. They were instructed to read the words as quickly as possible while maintaining safe control over the vehicle. The first page of text was displayed 60 s into the second drive and a new page of text was displayed every 13 s. The lead vehicle began braking 1.5 s after the seventh page appeared.

The Cognitive-distraction task was the complex spatial navigation task used in Task 5 (Cognitive Distraction). In this task, participants were given directions to three different restaurants and then asked questions about the locations of those restaurants. Whereas the directions to the restaurants were a series of three left or right hand turns at intersections, the questions asked about locations in terms of North, South, East, and West. Before the second drive, participants in the cognitive-distraction condition were shown a map (see Figure 9.3) that displayed the eight potential restaurant locations resulting from the three combinations of right vs. left turns. These participants were also provided with an example, wherein the text-to-speech voice presented the following message:

> *You are traveling north. If you turn at the next intersection you can reach three restaurants. To get to one restaurant, The <u>Bawston Sea Party</u>, turn <u>right</u> at the next intersection, and then turn <u>left</u> at the following intersection. Finally, turn <u>left</u> into the parking lot of The <u>Bawston Sea Party</u>. To get to another restaurant, <u>Matt’s Place</u>, turn <u>left</u> at the next intersection, and then turn <u>right</u> at the following intersection. Finally, turn <u>left</u> into the parking lot of <u>Matt's Place</u>. To get to the last restaurant, The <u>Pizza House</u>, turn <u>left</u> at the next intersection, and then turn <u>left</u> at the following intersection. Finally, turn <u>right</u> into the parking lot of The <u>Pizza House</u>.*

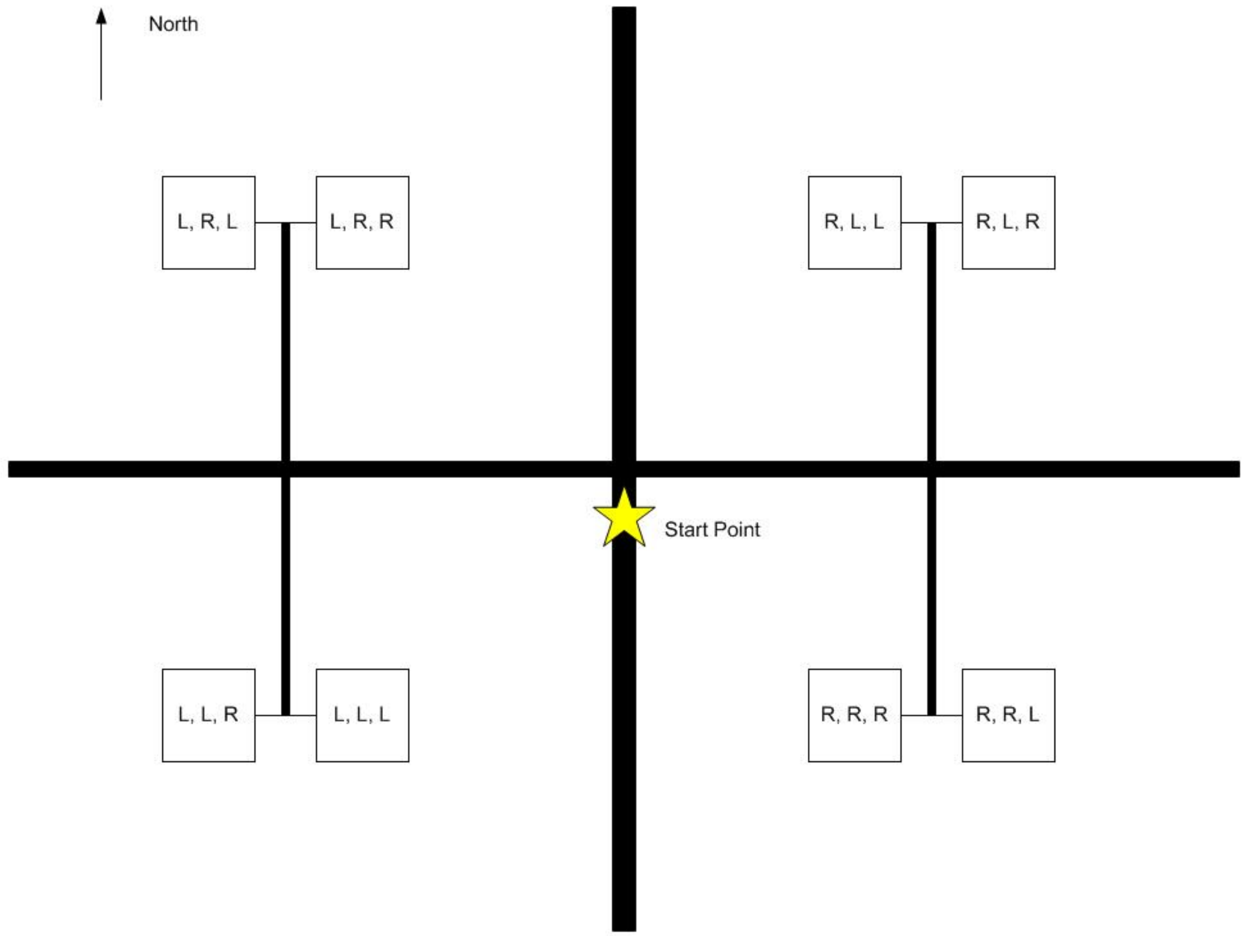

Figure 9.3. Map of the restaurant layout for the Spatial Navigation (Cognitive-distraction) Task

To be consistent with Task 5, the message was presented twice in order to provide participants with a greater opportunity to answer the questions. Participants were also provided with three practice questions (using the text-to-speech voice) before beginning the second drive:

1. Which restaurant has a parking lot you enter by turning west and is located to the east of your start point?

2. Which restaurant is located to the south of your start point and has a parking lot you enter by turning west?

3. Which restaurant is located to the east and north of your start point?

All questions used in this experiment were of the "complex" type (according to the definition of Task 5) because the questions required the participant to use two criteria to make a decision. Participants were instructed to always provide an answer in the form of a restaurant name and to provide an answer even if they were unsure whether it was correct.

During the second drive, a different message from the practice message was initiated approximately one minute into the drive. The only words that changed between messages were the left and right directions and the restaurant names. After the message was repeated twice, participants were asked the following question:

Which restaurant has a parking lot you enter by turning west and is located to the south of your start point?

The beginning of the lead-vehicle-braking event coincided with the “and” in the question sentence, which was 91 s after the message began. In all conditions the lead vehicle decelerated at a rate of -5 m/s^2.

Similar to the distraction conditions, the lead vehicle in the control condition began braking 151 s after the beginning of the second drive. In the High-expectancy condition (the third drive of the control group) the lead vehicle began braking 121 s after the beginning of the drive. All drives took place on a simulated oval highway track with four straight side segments. The lane width was 12-ft. and lane markers were clearly visible. The lead vehicle was a white sedan and was “yoked” to the host vehicle so that it would maintain a time-headway of approximately 1.8 s.

9.3 EXPERIMENT 1 RESULTS

A single factor between-subjects ANOVA was conducted on the Alerted BRT values from the second drive of the three distraction groups[2]. Alerted BRT was defined as the time interval between the instant that the FCW alert reached an imminent level and the moment that the participant first depressed the brake pedal. Figure 9.4 displays the Alerted BRT values as a function of the three distraction groups and the High-expectancy condition of the control group.

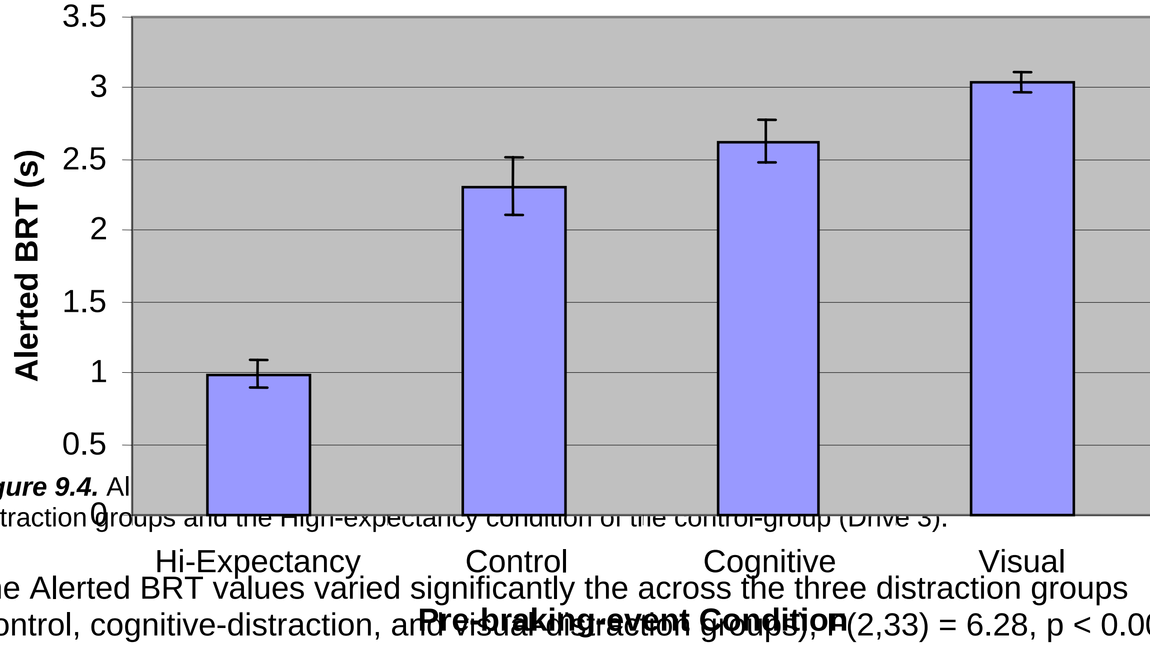

Figure 9.4. Al... sual-distraction groups and the High-expectancy condition of the control group (Drive 3).

The Alerted BRT values varied significantly the across the three distraction groups (control, cognitive-distraction, and visual-distraction groups), $F(2,33) = 6.28$, $p < 0.005$. The visual-distraction group (3.05 s) responded later than the control (2.31 s), $t(22) = 3.56$, $p < 0.001$, and cognitive-distraction (2.63 s) groups, $t(22) = 2.50$, $p < 0.005$ (2-tailed test). The difference between the cognitive-distraction and control groups approached significance, $t(22) = 1.28$, $p = 0.11$. A paired-comparison t-test was conducted within the control group to investigate the difference between Alerted BRT values in the second (surprise) and third (high-expectancy) drives. These participants responded earlier during the high-expectancy drive (0.99 s) than during the drive prior (2.31 s), $t(11) = 6.88$, $p < 0.0001$. All twelve participants displayed an earlier Alerted BRT during the high-expectancy drive than the surprise drive.

Figure 9.5 displays the participant's response times as a function of the four conditions, broken down in terms of the different components of the response: imminent alert response time[3], accelerator release time (ART), and BRT. Although the same FCW algorithm was used across conditions, there was a significant difference between the imminent alert response times across the three groups, $F(2,33) = 3.31$, $p < 0.05$. Using 2-tailed t-tests, the control group (0.74 s) was warned significantly earlier than the visual-distraction group (0.63 s), $t(22) = 2.46$, $p < 0.05$ and the difference between the

[2] It therefore did not include the high-expectancy condition (Drive 3) of the control group
[3] The imminent alert response time is defined as the time interval between when the imminent alert is issued and the time that the lead vehicle began braking.

control and … t(22) = 1.88, p = .07. The … e two control group drives …

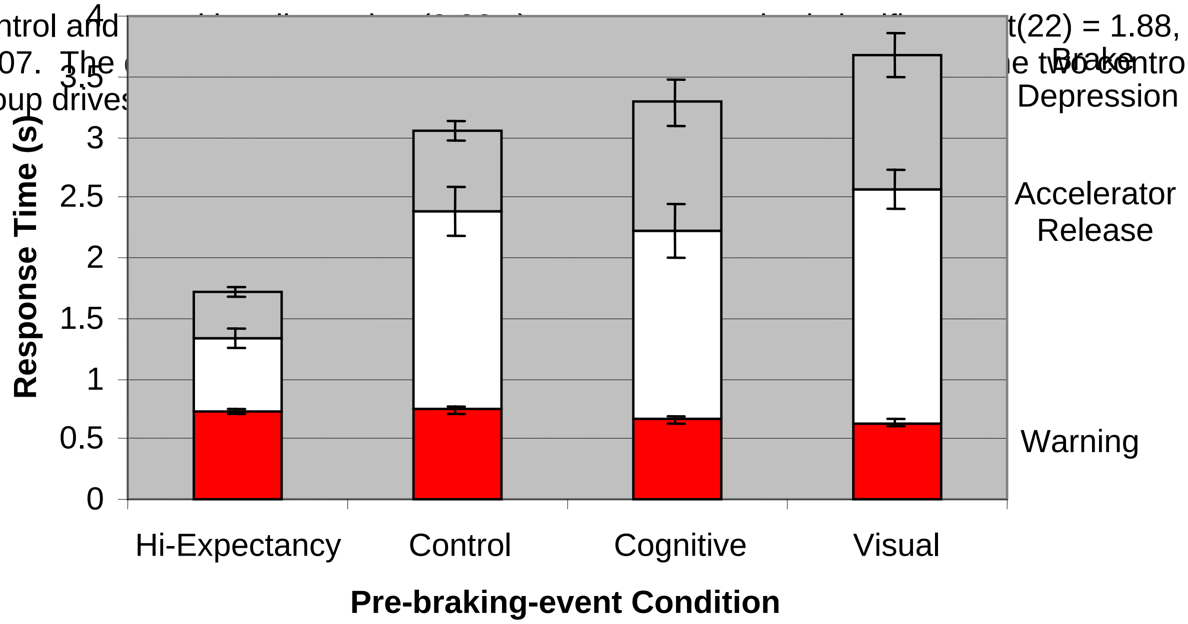

Figure 9.5. Response Times (brake depression, accelerator release, and warning activation) as a function of the control group, cognitive-distraction, and visual-distraction groups and the High-expectancy condition of the control-group (Drive 3).

Alerted ART is defined as the interval between the imminent FCW alert and the moment that the participant has removed pressure from the accelerator pedal. An ANOVA was also conducted on the Alerted ART responses for the three groups. Alerted ART responses did not differ significantly across the three groups, $F(2,33) = 0.96$, $p = 0.39$. However, within the control group, participants released the accelerator earlier on their second exposure (Hi-Expectancy: 0.61 s) than they did on their first exposure (1.64 s), $t(11) = 4.99$, $p < 0.0005$.

The final component of the response time is the pedal transition time, which is the time interval between the accelerator release and the first moment of brake depression. The ANOVA conducted on the pedal transition times revealed differences between the three groups that approached statistical significance, $F(2,33) = 2.33$, $p = 0.11$. Further contrasts revealed that the control group (0.67 s) transitioned significantly faster than the cognitive-distraction (1.06 s), $t(22) = 1.89$, $p < 0.05$, and visual-distraction groups (1.11 s), $t(22) = 2.27$, $p < 0.05$. Within the control group there were also significant differences between the pedal transition times of the first (0.67 s) and second (0.38 s) exposures, $t(11) =3.04$, $p < 0.01$.

9.4 EXPERIMENT 1 DISCUSSION

As hypothesized, the reaction times of the two distraction groups were slow compared with typical reaction times cited across the literature. The visual distraction group braked in response to the alert an average of 740 msec faster than the control group and although not statistically significant, the cognitive distraction group braked in response to the alert 320 msec faster than the control group. The most surprising result was how long it took participants with no explicit distraction to respond to an urgent and threatening event during their first exposure. Even when the drivers were not provided with any explicit distraction task, the average ART was 2.39 s. In a similar experiment Lee, McGehee, Brown, and Reyes (2002) recorded an average ART of 1.03 s for non-distracted drivers first exposure to an alerted braking event.

Given that drivers in this experiment responded with an average ART of 1.34 s during their second exposure (high-expectancy), it is likely that low-expectations of the braking event may account for the uncharacteristically long control group reaction times during the first exposure. Participants were informed that the purpose of the first two trials was to provide participants training with the driving simulator and distraction task (if present). During the first trial, the lead vehicle maintained a reasonably constant time-headway in front of the subject vehicle and nothing eventful occurred for the full 5-min duration. Halfway through the expected 5-min duration, the second drive was abruptly concluded with the braking event. It may be reasonable to hypothesize that the extremely low-levels of expectation and the lack of change in lead-vehicle headway combined to produce an inattentive driver. This explanation is consistent with the predictions of the Yerkes-Dodson (1908) Law, where performance is expected to decline when the task demand is extremely low. It is also consistent with the results of Stager, Hameluck, and Jubis (1989) who observed degraded vigilance in air traffic control performance during low task demand.

The constant time-headway may have also contributed to drivers responding slowly to the lead-vehicle braking event. In a similar experiment that was conducted in support of the ACAS FOT program in which the time-headway varied sporadically, the average BRT for drivers who were visually distracted was approximately 1.92 s for an imminent display without a cautionary level (Smith, 2002). This was 0.41 s earlier than the drivers in this experiment who were not provided with an explicit distraction task. Across these two studies, this difference may suggest that the drivers who followed a vehicle with greatly varying speed (but without an imminent braking event) were more prepared to respond to the lead-vehicle braking event than the drivers who followed a vehicle of constant speed. This may have occurred because drivers were constantly aware of the possibility of needing to respond to the lead vehicle. An alternative explanation is that the speed-variation of the lead vehicle in the Smith study provided drivers with some exposure to the cautionary stages of the FCW system, which may have helped prepare them to respond to the imminent alert. The longer reaction times of the drivers who experienced an imminent-only alert supports this explanation. Another critical difference between these experiments is that whereas time-headway was fixed in this experiment, in Smith study the drivers could select their own time-headway. The Smith study revealed a very strong correlation between the time-headway at the onset of the lead-vehicle braking event and the BRT ($r = 0.847$). The average time-headway at the onset of the lead-vehicle braking event was slightly shorter (1.6 s) in the Smith study than in this experiment (1.8 s). The instructed host-vehicle speed in the Smith study was also slower (45 mph) than it was in this experiment, which may have also contributed to the BRT difference. The average range to the host-vehicle in the Smith study was 34 m compared with the average range to the host-vehicle in this study of 52 m. At this shorter range, the optic flow resulting from the -5 m/s^2 lead-vehicle deceleration would have been far more salient at 34 m rather than 52 m. The large BRT differences between these two experiments suggest that range or time-headway to the lead-vehicle and the variability in lead-vehicle speed may be important variables for predicting the driver's BRT.

The comparison between the first (low-expectancy) and second (high-expectancy) trials revealed a large effect of the driver's expectations that almost overshadowed the effect of the distraction task. Whereas the visual distraction task produced a 7.5 and 32 percent increase in Alerted ART and BRT values over the control group, within the control group the effect of low expectancy was a 150 percent increase in both Alerted ART and Alerted BRT. Although this experiment revealed that average Alerted BRT values can range between the extremes of 1 and 3 s, it raises questions about the effect of the driver's state of alertness. A driver who does not appear to be distracted from the driving task may still be inattentive and require more time to respond to a warning. The long response times that were observed in the control group may be an artifact of the lack of danger inherent in the driving simulator, however, alternately they could also represent a serious threat to the driver that may exist on real roadways. If valid, this result may suggest that an intelligent collision warning system should not only take into account the driver's state of attention allocation, but also the demand of the driving task (both high and low) and the previous behavior of the lead vehicle. A relatively constant-speed lead vehicle at a large headway for long durations of time may "lull the driver into a false sense of security" that inhibits the driver's ability to react to even relatively intrusive warning stimuli.

Driver expectations are likely to be influenced by the uncertainty of the lead vehicle behavior. The effect of stimulus uncertainty on reaction time has been well documented in the literature (Wickens, 1992). For example, Naatanen and Koskinen (1975) observed a 40% increase in reaction times when stimuli were presented on only one out of every four trials compared with a presentation on every trial. If it is assumed that the lack of lead-vehicle activity preceding the braking event is training the driver that a braking response is unlikely, it would be reasonable to predict long reaction times. Olson and Sivak (1986) observed a 67% increase in BRT for braking in response to an unexpected obstacle compared with braking in response to an expected light.

Another factor that may have contributed to the control group's long reaction times to the event was the fact that they were warned significantly later than the two distraction groups[4]. However, although the later warnings of the control group may have contributed to the long event BRT values of the control group, the small magnitude (approximately 100 ms) of this change cannot completely account for this result. It also fails to account for the long Alerted BRT values (measured from the moment of the imminent alert rather than the braking alert), because the imminent-alert warning time is factored out of the Alerted BRT measurement.

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[4] This effect may have resulted from the participants in the control group maintaining a speed of closer to 65 mph than the distracted groups.

An analysis of mean absolute TLC[5], SDLP[6], and Lane RMS error revealed that the visual distraction task significantly degraded lane-keeping performance ($p < 0.01$) during the minute that preceded the lead-vehicle braking event compared with the control and cognitive distraction groups (see Figure 9.6). Note that, although it is not significant, the steering entropy is showing the opposite trend to that normally cited in the literature (Boer, 2001). If this finding was statistically significant, the direction of this difference would be difficult to explain. The cognitive distraction task did not significantly change lane-keeping performance during this same period for any of these dependent measures. This finding that cognitive distraction had little effect on lane-keeping performance is consistent with the results of the Horrey and Wickens (2004) meta-analysis and may suggest that lane keeping is a predominantly visual task that requires relatively little cognitive attention.

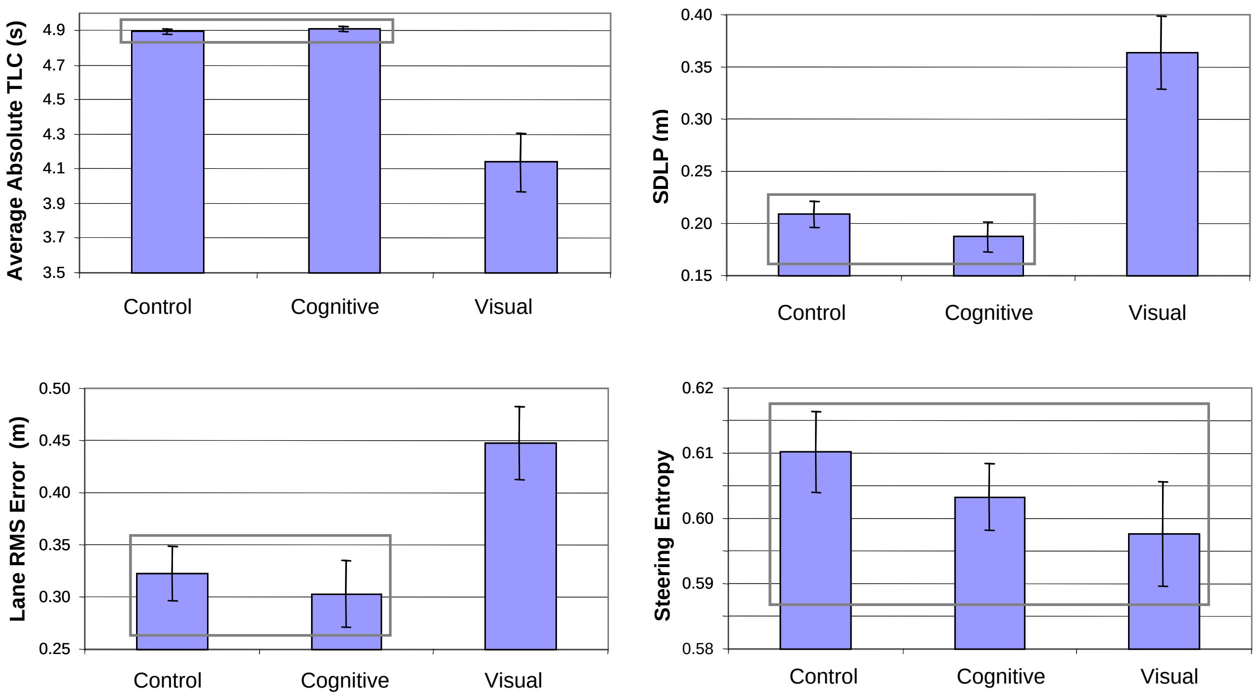

Figure 9.6. Lane-keeping performance metrics (mean absolute TLC, SDLP, lane RMS error, and steering entropy) for the 60 s preceding the lead-vehicle braking event as a function of the distraction group (Control, Cognitive, and Visual). The gray boxes contain measures that are not statistically distinct ($\alpha = 0.05$). Whereas the mean absolute TLC, SDLP, and lane RMS error measures reveal significant differences between the control and visual-distraction group, steering entropy does not ($p < 0.01$). The control and cognitive-distraction groups are not significantly different ($\alpha = 0.05$) for any of the four lane-keeping metrics.

Although not statistically significant ($p = 0.11$), the numerical difference between the control group's (first exposure) and the cognitive distraction group's Alerted BRT values was in the expected direction. The magnitude of Alerted BRT difference between the

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[5] The mean of the absolute value of the Time to Lane (TLC) crossing
[6] Standard deviation of Lane position

cognitive- and non-distraction groups (320 ms) was similar to that cited in the Lee, Caven, Haake, and Brown (2001) study, where they observed an ART difference of 310 ms between a speech-based e-mail task and no-distraction task. The repeated-measures design of the Task 5 experiment that uses the same cognitive distraction manipulation is a more powerful test of this effect. Compared with the results of the Horrey and Wickens (2004) meta-analysis, the difference between the cognitive distraction group and the control group was actually greater than the average effect of cell phones (130 msec) found across studies. This may suggest that this experiment used insufficient power to measure an effect of this magnitude. One possible explanation for why this effect may be relatively small is that cognitive distraction cannot be easily manipulated in an experiment. Although cognitive distractions can be provided to the participants, there is no way to ensure that these participants engage in the task and the level of engagement in the cognitive distraction task may vary widely across participants. There is also no way to ensure that the control group is not cognitively distracted and it is actually quite likely that the control group was at least to some extent cognitively distracted. When faced with a relatively uninspiring task that did not require their full attention, it is likely that participants began to mentally occupy themselves, providing an implicit cognitive distraction that could not be controlled. In this regard, the second exposure of the control group may be a more valid representation of non-distracted driving, because the certainty of the upcoming braking event influenced drivers to pay more attention to the lead vehicle.

9.5 EXPERIMENT 2 METHOD

The primary objective of Experiment 2 was to observe behavior and collect subjective usability judgments in response to different methods of adapting the safety warning systems. Due to the limitations in resources and time, this Experiment focused on adaptive FCW and LDW systems because these systems ares most likely to provide benefit to distracted drivers (see Task 9A literature review). The interface for the FCW system was not changed from Experiment 1 (see Section 9.2.2), however, the LDW interface was added to the display system. The interface for this system is displayed in Figure 9.7 and occupied the same space as the FCW display. The auditory stimulus for the imminent LDW alert was a half second recording of a vehicle traveling over rumble strips.

Figure 9.7. The five states of the LDW system on the HUD.

Because the real-time methods for measuring distraction are being developed in parallel with this task and have not yet been established, the countermeasures used the presence or absence of a distraction task as the criteria for adaptation. Using this criteria also provided participants with a consistent experience in this experiment. Three candidate methods of adaptation were developed and applied to the FCW and LDW systems. These methods of adaptation were:

Timing – The timing of the cautionary and imminent alerts was changed as a function of the presence of the distraction task. The rationale behind this adaptation is that distracted drivers may need more time to respond to a warning than non-distracted drivers. For the FCW system, for both cautionary and imminent alert algorithms, the predicted Alerted BRT was 1 s during intervals without distraction tasks and 3 s during intervals with distraction tasks[7]. For the LDW system, the TLC threshold for the cautionary alert changed from 1 s (without a distraction task) to 3 s (with a distraction task) and the imminent alert from 0.1 s (without a distraction task) to 1 s (with a distraction task) [8].   Large differences in criteria were selected for the two distraction states in order to make the adaptation more observable in this experiment.

Suppress – In the Suppress adaptation, whereas the visual-only cautionary alert behaves consistently whether the driver is distracted or not, the imminent alert is suppressed when the driver is not engaged in the distraction task. The cautionary alerts

[7] The nominal BRT value was 1.5 s for the other three conditions (suppress, auditory, non-adaptive).
[8] The nominal TLC value for a cautionary alert was 2 s and for an imminent alert was 0.5 s for the other three conditions (suppress, auditory, non-adaptive).

were not suppressed because they were visual-only presentation and appeared to evoke less annoyance in the ACAS FOT. This implementation was applied consistently across the FCW and LDW systems. The rationale behind this adaptation is that when drivers are in control and attentive, they may have greater ability to determine the level of threat than the collision warning systems and therefore do not require imminent warnings. Because cautionary alerts are more of a status indication than a warning per se, they were preserved in order to provide consistency between conditions. Suppressing imminent alerts when the driver is attentive may provide a useful method for reducing the number of inappropriate warnings.

Auditory – The nature of the auditory warning stimuli was changed as a function of the presence of a distraction task. Cautionary warnings were accompanied with auditory voice messages (“vehicle braking”, “drifting left”, and “drifting right”) when a distraction was present. However, no auditory stimulus was provided for either the cautionary or imminent stages when the driver was not being distracted. Tonal stimuli tend to be used for warning systems rather than voice messages, because they tend to be less annoying (Lerner, Dekker, Steinberg, & Huey, 1996a) and require less time to respond (Kiefer, LeBlanc, Palmer, Salinger, Deering, & Shulman, 1999). However, the advantage of voice messages over tonal messages is that they are capable of communicating more specific information. If a driver is distracted (e.g., looking away from the forward scene) and therefore outside of the control loop, there may be a greater benefit of communicating more precise information, such as “the lead vehicle is braking” vs. “there is a forward threat”. This is especially likely if the information being communicated represents a change in the environment that the driver may temporarily be unable to perceive. Although voice messages are more likely to annoy the driver, this effect may be minimized if the message is informative (providing information to which the driver does not currently have access). In order to mitigate against the effect of voice messages requiring more time to respond, the voice messages were made relatively short (approximately 900 ms) and were accompanied with the cautionary rather than imminent stage. The rationale behind suppressing the audible during attentive driving is similar to the rationale for suppressing the imminent warnings, however, when only the auditory stimuli is suppressed the driver can still observe an imminent state visually. Drivers in the ACAS FOT appeared to be more tolerant of visual-only warning stimuli.

9.5.1 Participants

The participants were the same as those used in the Visual and Cognitive distraction conditions of Experiment 1. The control group was dismissed at the completion of Experiment 1 and took no part in Experiment 2. For the participants who continued into Experiment 2, the transition between Experiments occurred seamlessly, with only a few minutes between the second drive of Experiment 1 and the first drive of Experiment 2. Participants remained in the same distraction group (visual or cognitive) that they had experienced during Experiment 1.

9.5.2 Apparatus

The apparatus was the same as that used in Experiment 1, except that a LDW system was included in Experiment 2.

9.5.3 Design

A mixed factorial design was used that exposed the two ***Distraction Type*** (Visual and Cognitive distraction) to four levels of ***Adaptation*** (Non-adaptive, Timing, Suppress, and Auditory). One type of adaptation was used for each of the four drives and in each drive the same adaptation was applied to both ***Warning Systems*** (FCW and LDW). Participants experienced the two levels of ***Distraction Presence*** on each drive: two segments in which the distraction task was presented and two segments in which no distraction task was present and three levels of lead-vehicle ***Deceleration Rates*** ($-1\ m/s^2$, $-3\ m/s^2$, and $-5\ m/s^2$). Whereas the order of the Timing, Suppress, and Auditory adaptations was counterbalanced across participants, all participants experienced the Non-adaptation condition during the first drive. In order to provide participants with a consistent basis of comparison, they were informed that the warning systems on the first drive would not be adaptive.

The dependent measures were the subjective ratings that participants provided for the questions displayed in Figure 9.8. After each drive, participants answered a page of questions, half of which asked about the FCW system, and half of which asked about the LDW system. The questionnaire asked participants to rate the annoyance, usefulness, timing, trust, and self-confidence of the warning systems. In addition the questionnaire asked participants what percentage of alerts seemed unnecessary, and whether the adaptation seemed noticeable. If participants indicated that the adaptation was noticeable, they were then asked how effective the adaptation was and to list any likes and dislikes they had in regard to the adaptation. After participants had experienced all four drives, they were asked to rank the four drives from best to worst based on their preference for the system behavior. Participants ranked the drives separately for the FCW and LDW systems.

9.5.4 Procedure

After participants had been debriefed from Experiment 1, they were then informed about the nature of Experiment 2. The experimenter described the behavior of the FCW and LDW warning systems in detail and informed participants that the purpose of the experiment was to collect feedback about the adaptive warning systems. To ensure that participants knew what aspects of the simulation to attend to, the experimenter showed the post-drive questionnaire to them. Participants were instructed to drive safely at 65 mph, but that they could test the warning systems to some extent in order to make informed judgments about the adaptations. The experimenter stressed that the purpose of the exercise was not to evaluate their performance but instead to provide them with an experience of the adaptive systems so that they could provide meaningful feedback.

Participant Number: ___

Drive No. 1:
No Adaptation

Forward Collision Warning (FCW)

1. During your last drive, what percentage of the FCW alerts seemed unnecessary?

2. Rate the degree to which the FCW system **ANNOYED** you:

   Not annoying at all … Extremely annoying
   1 2 3 4 5 6 7

3. Rate the degree to which the FCW system was **USEFUL** to you:

   Not useful at all … Extremely useful
   1 2 3 4 5 6 7

4. Rate the **TIMING** of the FCW alerts:

   Far Too Early … Just Right … Far Too Late
   1 2 3 4 5 6 7

5. Rate the degree to which you **TRUSTED** the FCW system to help you avoid a rear-end collision, compared to trusting your own abilities:

   Not at all … Completely
   1 2 3 4 5 6 7 8 9 10

6. Rate the degree of **SELF-CONFIDENCE** you had in your ability to stay in the lane when using the FCW system, compared to if you did not have it:

   Not at all … Completely
   1 2 3 4 5 6 7 8 9 10

7. Did the FCW alerts appear to respond differently when you were distracted compared to when you were not distracted?
   ☐ Yes → Answer questions 8, 9, and 10.
   ☐ No → Go to question 11.

8. Rate the **EFFECTIVENESS** of the FCW adaptation:

   Made it worse … No Benefit … Extremely Effective
   1 2 3 4 5 6 7 8 9

9. What, if anything, did you like about the FCW adaptation?

10. What, if anything, did you dislike about the FCW adaptation?

Lane Drift Warning (LDW)

11. During your last drive, what percentage of the LDW alerts seemed unnecessary?

12. Rate the degree to which the LDW system **ANNOYED** you:

    Not annoying at all … Extremely annoying
    1 2 3 4 5 6 7

13. Rate the degree to which the LDW system was **USEFUL** to you:

    Not useful at all … Extremely useful
    1 2 3 4 5 6 7

14. Rate the **TIMING** of the LDW alerts:

    Far Too Early … Just Right … Far Too Late
    1 2 3 4 5 6 7

15. Rate the degree to which you **TRUSTED** the LDW system to help you to maintain lane position, compared to trusting your own abilities:

    Not at all … Completely
    1 2 3 4 5 6 7 8 9 10

16. Rate the degree of **SELF-CONFIDENCE** you had in your ability to stay in the lane when using the LDW system, compared to if you did not have it:

    Not at all … Completely
    1 2 3 4 5 6 7 8 9 10

17. Did the LDW alerts appear to respond differently when you were distracted compared to when you were not distracted?
    ☐ Yes → Answer questions 18, 19, and 20.
    ☐ No → Drive number 2

18. Rate the **EFFECTIVENESS** of the LDW adaptation:

    Made it worse … No Benefit … Extremely Effective
    1 2 3 4 5 6 7 8 9

19. What, if anything, did you like about the LDW adaptation?

20. What, if anything, did you dislike about the LDW adaptation?

After Drive No. 4

Ranking the four Drives (FCW)

81. Please rank the last four drives from best to worst, based on your preference for the FCW system behavior:

    Best Drive No. ___
    Second Best Drive No. ___
    Third Best Drive No. ___
    Worst Drive No. ___

Ranking the four Drives (LDW)

82. Please rank the last four drives from best to worst, based on your preference for the LDW system behavior:

    Best Drive No. ___
    Second Best Drive No. ___
    Third Best Drive No. ___
    Worst Drive No. ___

Figure 9.8. The first (questions 1 to 20) and last (questions 81 to 82) pages of the post-drive questionnaire. Pages two, three, and four provided repetitions of the first page for the three subsequent drives.

All drives occurred on simulated highway terrain and used the same lead vehicle as Experiment 1 with the fixed 1.8-s time headway. Each drive lasted for approximately 12 min and was composed of four segments. Each segments contained 90 deg left and right turn sections, one straight section, and one s-curve section. Each segment also contained the three lead-vehicle deceleration rates. During segments 1 and 3 the driver was not distracted by the secondary task and during segments 2 and 4 the driver was distracted by the secondary task. This ensured that participants could experience both the distracted and non-distracted behaviors of the adaptive countermeasures. Rather than tying the adaptation of the countermeasures to the real-time assessment of driver-state, the adaptation was driven by whether the distraction task was present.

In order to ensure that participants were constantly engaged during the visual distraction task, the moment participants completed reading a page of words, a new page of words would appear. In the cognitive distraction task, participants listened to the message (playing twice) and were then asked as many questions as were required before they reached the end of the section. The number of questions ranged between four and eight, depending on how quickly participants answered the questions and the length of the messages.

9.6 EXPERIMENT 2 RESULTS

9.6.1 Objective FCW Data

9.6.1.1 Adaptive System Responses

Table 9.1 presents the adaptive system responses of the FCW system for the three methods of adaptation. The twenty-four drivers (of the combined two groups) experienced two repetitions of each lead-vehicle braking rate (-1 m/s^2, -3 m/s^2, and -5 m/s^2) by distraction presence (distracted, non-distracted) combination. The combination of two repetitions per subject provided a maximum of 48 alerts for each type of braking event. To assess the impact that the adaptive systems had on the alert behavior, the adaptive system responses were compared to nominal system responses during the same drive. In order to compare the performance of the adaptation with that of a non-adaptive system, a non-adaptive version (nominal) of the FCW and LDW systems ran in the background and was recorded. Although the participants did not experience this nominal system (unless they were on the non-adaptive trial), it provided a means of quantifying the effect of the adaptations. The three possible changes to the system were addition or subtraction of alerts (by the timing or suppress adaptations), change timing of alerts (by the timing adaptation), or change the nature of the auditory stimuli (by the auditory adaptation).

Table 9.1. Adaptive System Responses of the FCW cautionary and warning alerts as a function of adaptation, distraction presence, and deceleration rate.

		Timing		**Suppress**	**Auditory**	
		Distracted	**Non-distracted**	**Non-distracted**	**Distracted**	**Non-distracted**
FCW Caution	**- 1 m/s^2**	+ 43 alerts	-2 alerts		9 voice	
	- 3 m/s^2	+ 5 alerts *0.52 s earlier*	*1.4 s later*		48 voice	
	- 5 m/s^2				48 voice	
FCW Warning	**- 1 m/s^2**	+ 1 alerts	- 1 alerts	-1 alerts (all)		1 silent
	- 3 m/s^2	+36 alerts *6.0 s* earlier*	*0.58 s later*	-21 alerts (all)		48 silent
	- 5 m/s^2	*0.65 s earlier (all instant)*	-5 alerts *0.59 s later*	-47 alerts (all)		48 silent

Note. The numbers of alerts represent the number of alerts (out of a maximum of 48) that were added, suppressed, or changed as a consequence of adaptation in the two combined groups. The italicized text describes the timing change of the alert.
* This large timing change resulted from driver brake interventions

In several cases the timing adaptation not only adjusted the timing but also changed the number of alerts. For example, in response to the -3 m/s^2 distracted events, the timing adaptation provided cautionary alerts an average of 0.52 s earlier than when they would have otherwise occurred and provided an additional five cautionary alerts. This could occur because drivers could respond to the earlier timing-adapted alerts before a nominal alert would have occurred and therefore a nominal alert never became necessary. The timing change could only be evaluated in cases where both timing-adapted and nominal alerts occurred and not in situations where the adaptation either added or suppressed an alert. During the non-distraction segments, drivers frequently responded to the event before the adaptive timing threshold was reached. This led to the timing-adaptation alert suppressions. The timing adaptation had no effect on the -5 m/s^2 cautionary alerts because this high deceleration triggered both adaptive and nominal alerts instantly. Perhaps the largest effect of the timing adaptation to the cautionary alerts was that it added 43 distracted-cautionary alerts for the -1 m/s^2 condition. Whereas the suppress adaptation had no effect on the cautionary alerts by design, the auditory adaptation altered their behavior considerably, providing all drivers with at least four voice-auditory ("vehicle braking") cautionary alerts.

The adaptations had little effect on the -1 m/s^2 warning alert responses because so few warnings were issued for these less-severe events, however, the adaptations did have a measurable effect on the warning alerts in the higher-severity conditions. In response to the -3 m/s^2 braking events, the timing adaptation added 36 warnings during the distracted segments and suppressed 18 warnings during the non-distracted segments. In response to the -5 m/s^2 braking events, the timing adaptation presented all warnings instantaneously during the distracted segments, providing these warnings an average of 0.65 s earlier than a nominal system would have done in the same situation. By design, the suppress adaptation suppressed all warnings during the non-distracted segments and the auditory adaptation suppressed the auditory stimuli for all warnings during the non-distracted segments.

9.6.1.2 Driver Reaction Times to the Lead-Vehicle Braking Events

Accelerator Release Times (ART) and Brake Reaction Times (BRT) were recorded in response to the lead-vehicle braking events. Note that the values examined in this analysis measured the response times from the moment that the lead vehicle began braking rather than the moment that the alert was presented. A 2 (***Distraction Type***) x 4 (***Adaptation***) x 2 (***Distraction Presence***) x 2 (***Deceleration Rate***) mixed ANOVA was conducted on both the ART and BRT measures. The -1 m/s^2 braking events were excluded from this analysis because drivers usually began braking before even a cautionary alert was issued and so the response times are difficult to interpret meaningfully. Table 9.2 displays the results of the AVOVA.

The ART measure exhibited an interaction between distraction type and distraction presence. Figure 9.9 shows how the effect of distraction changes as a function of the type of distraction. Whereas the visual distraction task delayed accelerator releases during the non-adaptive, suppress, and auditory adaptations ($p < 0.05$), the cognitive distraction task only affected the timing adaptation. Rather than delaying the releases, the timing adaptation produced earlier accelerator releases ($p < 0.05$) when the driver was distracted. This expediting effect can be explained by the timing adaptation over-compensating for the influence of distraction. Table 9.1 revealed that the timing adaptation alerted drivers almost 2 s earlier in response to the -3 m/s^2 braking events when drivers were distracted (0.5 s earlier when distracted and 1.4 s later when not distracted). This 2-s difference may have been excessive because the cognitive distraction task did not affect the ART values in the non-adaptive trials and the visual distraction task delayed ART values by less than 400 msec (as shown in Figure 9.9). In the visual distraction group, it is also evident that the timing adaptation delayed accelerator releases more than the other adaptations when the driver was not distracted ($p < 0.05$). This non-distracted (visual) comparison may be especially informative between the timing and suppress adaptations because it supports McGehee and Brown's (1998; cited in Lee, McGehee, Brown, and Reyes, 2000) claim that late warnings may be worse than having no warning at all.

Table 9.2. The results of the ANOVA on the ART and BRT responses to the -3 m/s^2 and -5 m/s^2 braking events

Effect	Measure	df	F value	p value
Distraction Type x Adaptation x Distraction Presence	ART BRT	3,66	2,69 1.84	0.053 0.148
Distraction Type x Distraction Presence	ART BRT	1,22	6.04 4.10	< 0.05 0.055
Adaptation x Distraction Presence x Deceleration Rate	ART BRT	3,66	14.40 13.75	< 0.001 < 0.001
Distraction Presence x Adaptation	ART BRT	3,66	37.75 22.85	< 0.001 < 0.001
Adaptation x Deceleration Rate	ART BRT	3,66	11.85 10.16	< 0.001 < 0.001
Adaptation	ART BRT	3,66	19.49 13.09	< 0.001 < 0.001
Distraction Presence	ART BRT	1,22	0.31 23.42	0.583 < 0.001
Deceleration Rate	ART BRT	1,22	435.68 946.94	< 0.001 < 0.001

Figure 9.10 displays the Adaptation x Distraction Presence x Deceleration Rate interaction on the accelerator release and brake reaction times for the visual-distraction group. Because drivers usually released the accelerator pedal before the warning alerts for the -3 m/s^2 braking events, it is more likely that the cautionary alerts affected the drivers responses to the -3 m/s^2 braking events. For this reason, the cautionary alert timing is shown for the -3 m/s^2 braking events. Drivers usually released the accelerator pedal after the warnings for the -5 m/s^2 braking events, so the lower cell (-5 m/s^2 braking events) displays the warning alert timing. Distracted drivers received timing-adapted cautionary alerts almost immediately following the -3 m/s^2 braking events. Likewise, distracted drivers received timing-adapted warnings almost immediately after the -5 m/s^2 braking events. However, when the driver was not distracted, the accelerator releases and warnings tended to occur almost simultaneously for the -5 m/s^2 braking events. By design, the suppress adaptation suppressed all imminent alerts.

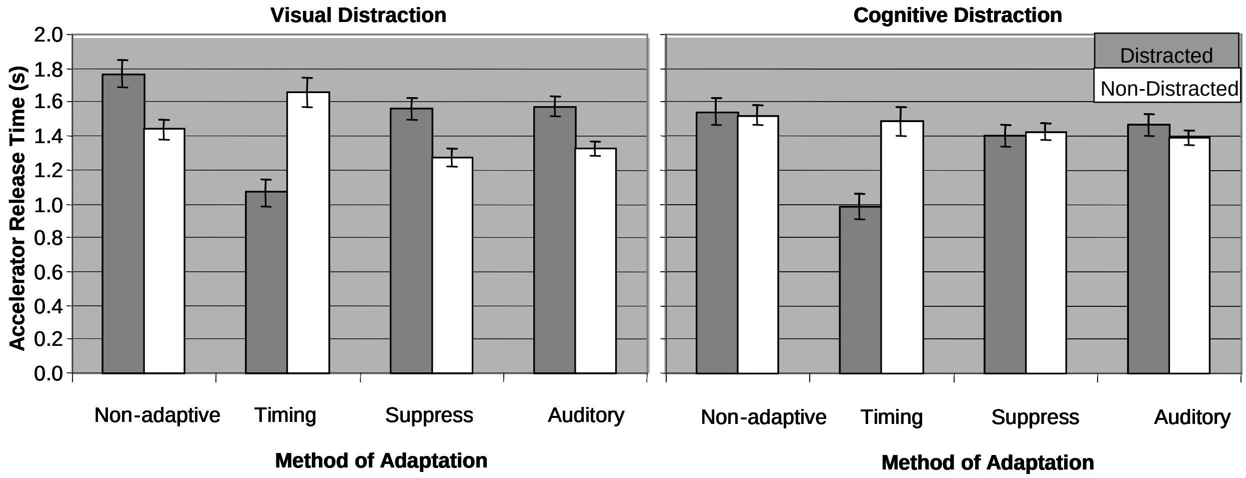

Figure 9.9. The Distraction Type x Distraction Presence x Adaptation interaction on Accelerator Release Time Values. Although this interaction did not reach statistical significance ($p = 0.053$), this plot may help to explain the Distraction Type x Distraction Presence interaction.

Although drivers released the accelerator faster when they were distracted ($p < 0.05$) in response to the -5 m/s^2 braking events, the difference in BRT was not significant. This trend of ART being a more sensitive measure than BRT appears to be quite consistent in these results and may reflect the compensatory mechanism of drivers transitioning their feet more quickly when the situation is more urgent. The difference between ART and BRT measures is particularly pronounced in the suppress adaptation. Drivers displayed faster non-distracted ART and BRT responses ($p < 0.05$) to the -3 m/s^2 braking events and faster non-distracted ART responses ($p < 0.05$) the -5 m/s^2 braking events, however, the BRT responses to the -5 m/s^2 braking events showed the opposite trend ($p < 0.05$). During the distracted segments of the suppress-adaptation trials, drivers transitioned between pedals quickly, perhaps indicating that the less frequent warnings were more effective at eliciting an urgent response. Consistent with Figure 9.9, drivers responded (both ART and BRT) more slowly to the non-distracted timing-adapted alerts than to the absence of alerts of the suppress adaptation for the -3 m/s^2 condition ($p < 0.05$). This trend was also true for the ART responses to the -5 m/s^2 condition ($p < 0.05$). The responses to the non-adaptive and auditory adaptations appear to be similar and the absence of a statistically significant difference suggests that this adaptation had little effect on driver performance. Appendix A (Pair-wise Comparisons Between Reaction Times) provides a complete list of statistically significant contrasts.

Figure 9.11 displays the Adaptation x Distraction Presence x Deceleration Rate interaction on both the accelerator release and brake reaction times for the cognitive-distraction group. The most apparent differences between the two types of distraction are that the effects of distraction presence on -3 m/s^2 ART values. The effect of distraction that is present in the visual-distraction group is not mirrored in the cognitive-distraction group (except for the reversed effect in the timing adaptation). Another difference between the distraction groups is that the absence of an alert in the non-distracted segments of the suppress adaptation appears to be more harmful for the higher lead vehicle decelerations.

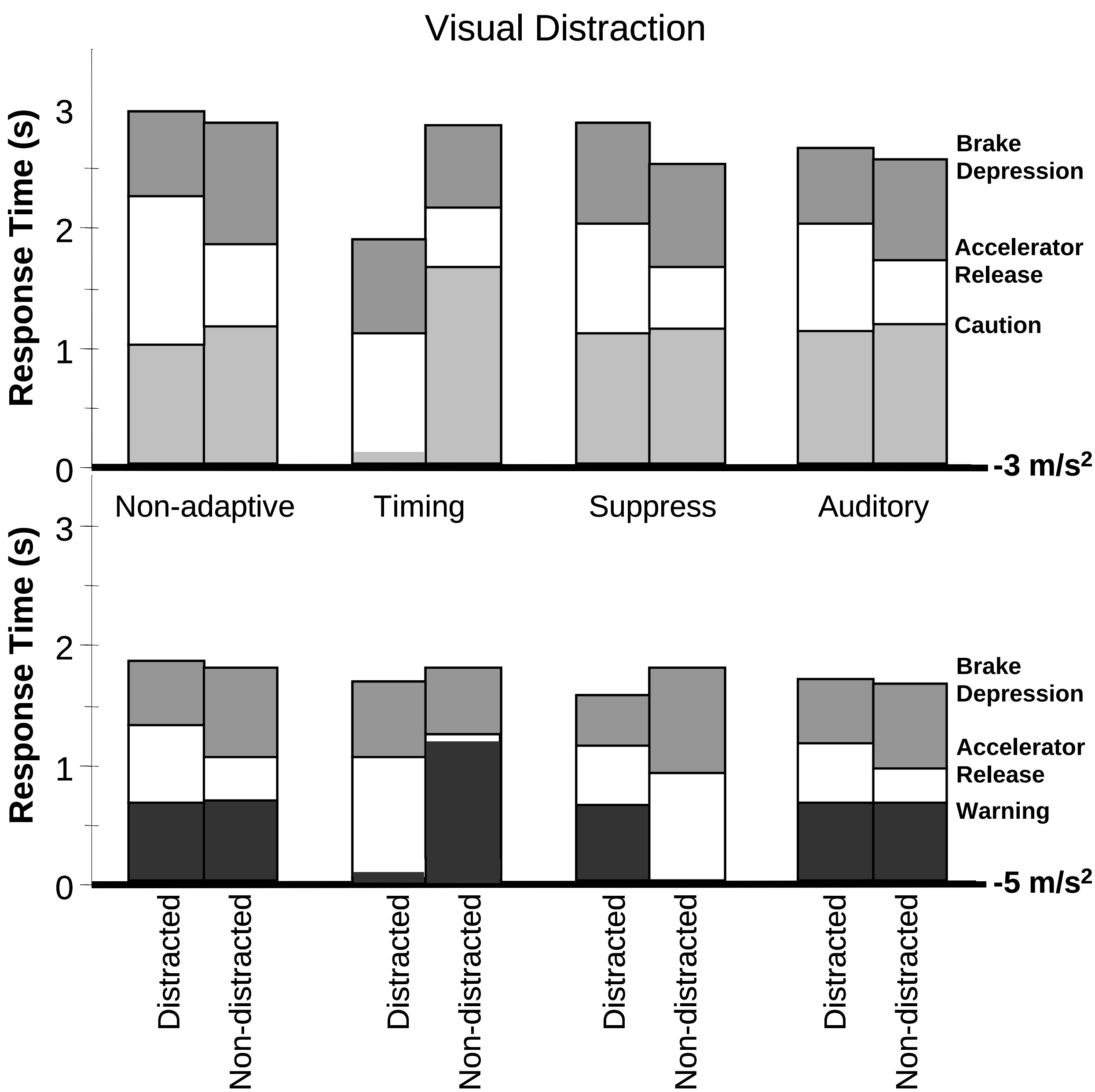

Figure 9.10. Driver responses (accelerator releases and brake depressions) in response to the -3 m/s^2 (top) and -5 m/s^2 (bottom) braking events for the visual-distraction group, four levels of adaptation, and two levels of distraction presence (distracted vs. non-distracted). The cautionary response time is displayed in the -3 m/s^2 plot and the warning response time is displayed in the -5 m/s^2 plot. The white sections represent the Alerted ARTs (the time between the alert and the accelerator release), which are equal to the ART values minus the alert response times. The gray sections above the white represent the pedal transition times.

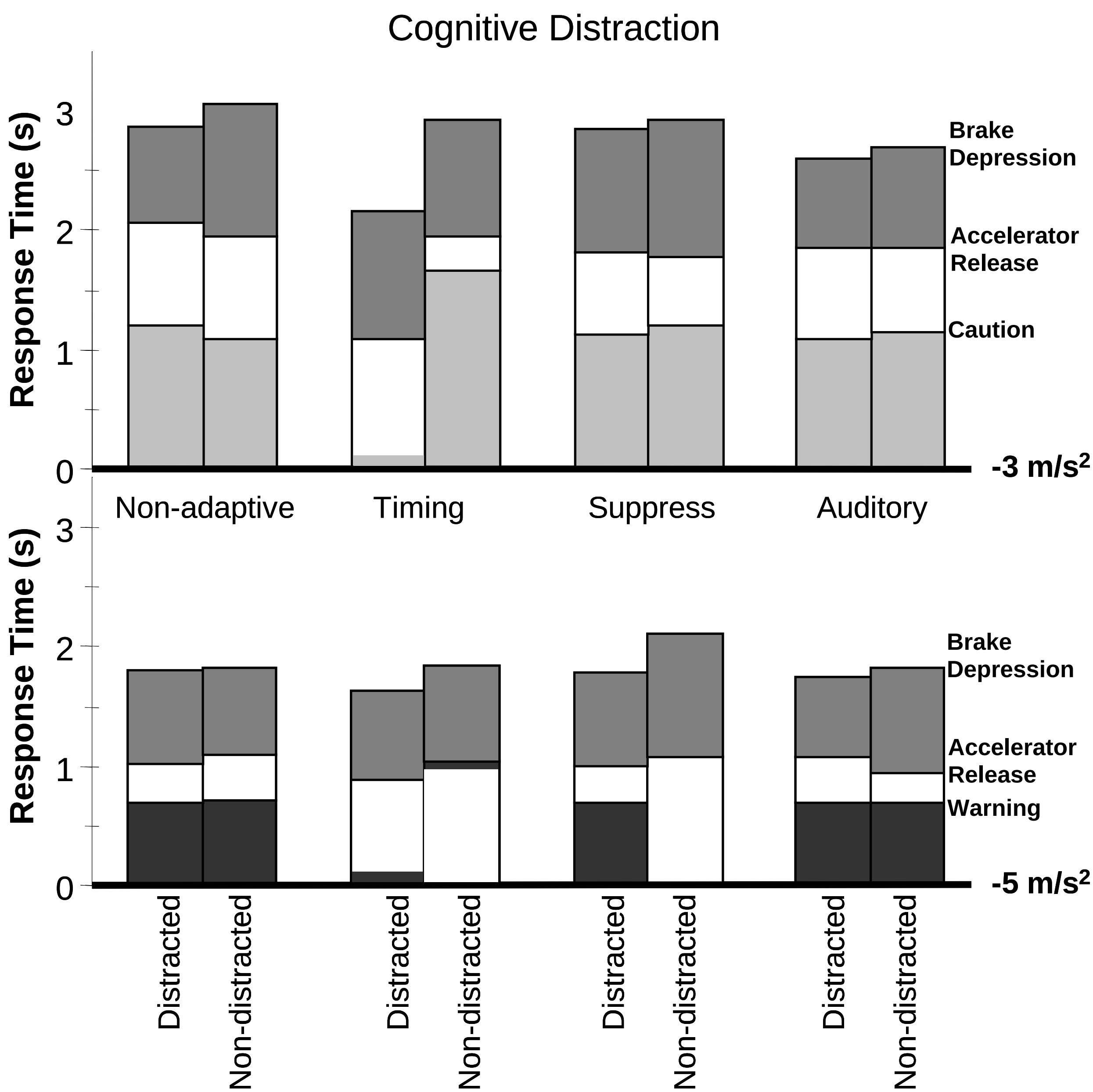

Figure 9.11. Driver responses (accelerator releases and brake depressions) in response to the -3 m/s^2 (top) and -5 m/s^2 (bottom) braking events for the cognitive-distraction group, four levels of adaptation, and two levels of distraction presence (distracted vs. non-distracted). The cautionary response time is displayed in the -3 m/s^2 plot and the warning response time is displayed in the -5 m/s^2 plot. The white sections represent the Alerted ARTs (the time between the alert and the accelerator release), which are equal to the ART values minus the alert response times. The gray sections above the white represent the pedal transition times.

9.6.2 Objective LDW Data

9.6.2.1 Adaptive System Responses

One participant in the visual-distraction group displayed disproportionately poor lane-keeping performance while she was distracted. Whereas the average number of LDW cautionary alerts for all other participants during visual-distraction driving segments was 16.9 (SD = 12.1), this participant received an average of 59.5 (over 3.5 standard deviations above the mean). For this reason, her data were excluded from all lane-keeping-related analyses.

Table 9.3 displays the adaptive system responses of the LDW system for the three methods of adaptation. This table demonstrates that whereas most drivers experienced the effects of the timing and auditory adaptations on the cautionary alerts, relatively few drivers experienced any changes that affected the warning alerts. For example, the suppress adaptation only influenced the alerts of four out of 24 subjects. This is due to the fact that cautionary alerts were far more prevalent than warnings, especially in the absence of any distraction.

Table 9.3. Adaptive System Responses of the LDW cautionary and warning alerts as a function of adaptation, distraction, and distraction group.

		Timing		**Suppress**	**Auditory**	
		Distracted	**Non-distracted**	**Non-distracted**	**Distracted**	**Non-distracted**
Visual	**LDW Caution**	+ 17.2 alerts per driver	-3.7 alerts per driver		10 voice alerts per driver	
	LDW Warning	+3, +3, +4 alerts (3 drivers)		-1, -1, -1 alerts (3 drivers)		1 silent alert (1 driver)
Cognitive	**LDW Caution**	+ 8.4 alerts per driver	-3.0 alerts per driver		10 voice alerts per driver	
	LDW Warning	+1, +1 alerts (2 drivers)	-1, -1 alerts (2 drivers)	-1 alert (1 driver)		1,1,3 silent alerts (3 drivers)

Note. Because all drivers were exposed to cautionary alerts, they alerts are averaged across drivers, however, because so few drivers experienced warnings, these warnings are presented on an individual basis.

A 2 (***Distraction Type***) x 4 (***Adaptation***) x 2 (***Distraction Presence***) mixed ANOVA was performed on the number of LDW cautionary alerts that participants received. The results of this analysis are displayed in Table 9.4. All interactions and main effects reached statistical significance. Figure 9.12 displays the average cautionary alert counts as a function of Distraction Type, Adaptation, and Distraction Presence.

Post-hoc pair-wise comparisons revealed that the visual-distraction task significantly increased the number of cautionary alerts for each type of adaptation ($p < 0.005$). The cognitive-distraction task, however, only increased the number of cautionary alerts for the timing adaptation ($p < 0.001$). The increase for the timing-adaptation in the cognitive-distraction group can be accounted for by the change in alert criteria rather than the change in the driver’s behavior. By comparing adapted alerts with nominal alerts, the change in the timing alert criteria added an average of 8.4 cautionary alerts per driver. The number of cautionary alerts significantly decreased during segments of cognitive-distraction in the non-adaptation condition ($p < 0.05$).

Table 9.4. The results of the ANOVA on the number of LDW cautionary alerts

Effect	df	F Value	p value
Distraction Type x Distraction Presence x Adaptation	3,66	8.57	< 0.001
Distraction Type x Adaptation	3,63	4.97	< 0.005
Distraction Type x Distraction Presence	1,21	45.44	< 0.001
Distraction Presence x Adaptation	3,63	44.55	< 0.001
Distraction Type	1,21	21.04	< 0.001
Distraction Presence	1,21	58.38	< 0.001
Adaptation	3,63	18.00	< 0.001

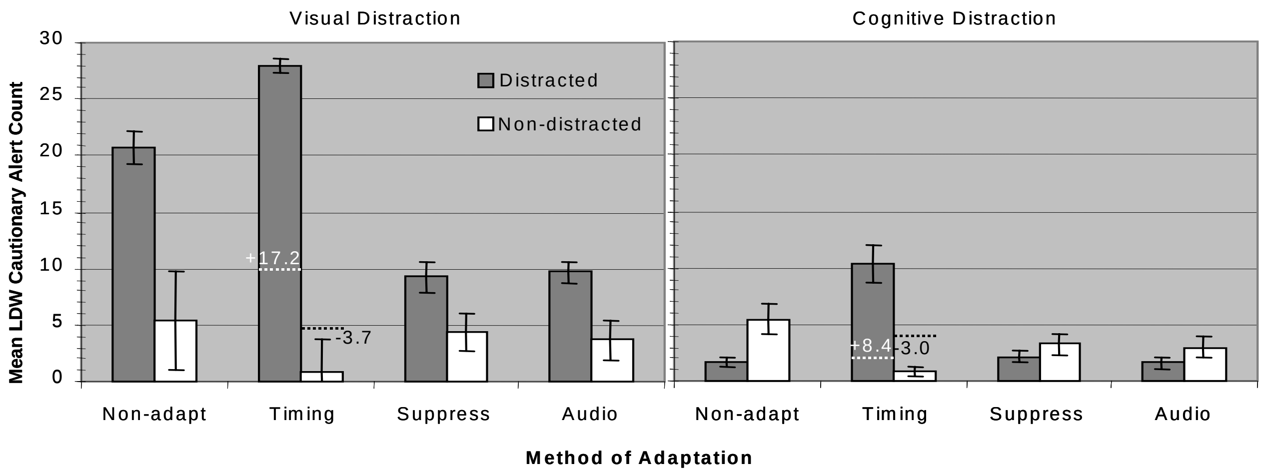

Figure 9.12. The mean LDW cautionary alert counts per driver as a function of adaptation, distraction presence, and distraction type. The dotted lines represent the mean number of cautionary alerts that would have occurred if the cautionary alert criteria remained nominal. The numbers next to the dotted line represent the mean number of cautionary alerts that were either added or subtracted from the nominal criterion.

Post-hoc pair-wise comparisons of the different adaptations revealed that during the visually-distracted segments the non-adaptive and timing conditions produced significantly greater LDW cautionary alert counts than the suppress and auditory conditions ($p < 0.05$). In the distraction segments of the cognitive-distraction group, the timing condition produced significantly greater LDW cautionary alert counts than the other three adaptation conditions ($p < 0.001$). During the segments of non-distracted driving (both visual and cognitive), the timing adaptation produced significantly fewer LDW cautionary alerts than the other three adaptation conditions ($p < 0.05$).

There were only three participants who displayed measurable changes of cautionary-alert timing during the non-distraction segments for the visual distraction group (0.5, 0.8, 0.9 s delays) and five participants for the cognitive-distraction group (0.3, 0.4, 0.6, 0.8, and 2.7 s delays). During segments of visual-distraction, cautionary-alert timing changes ranged from 0.2 to 0.5 s (adaptive alerts earlier than nominal) for the eleven participants, producing a mean of 0.36 s (SD = 0.02). During segments of cognitive-distraction, cautionary-alert timing changes ranged from 0.3 to 0.9 s for ten participants. However, half of the participants revealed timing changes of 0.3 s. The median alert-timing change for cognitive distraction was 0.41 s. Although the change in Time-to-Lane-Crossing (TLC) criterion was consistently used in the timing adaptation, the actual change in timing that resulted from this criterion change could vary because of drivers' actions between the timing-adapted and nominal alerts.

Visually-distracted participants received an average of 8.3 audible cautionary alerts during the auditory drive and cognitively-distracted participants received an average of 1.5 audible cautionary alerts during the auditory drive. Half of these drivers received 1 or fewer audible cautionary alerts.

The imminent LDW alert counts are displayed in Figure 9.13 as a function of distraction type, adaptation, and distraction presence. Drivers experienced relatively few imminent lane-departure warnings. The non-adaptive condition produced more imminent warnings than any of the other conditions, with eight out of eleven participants in the visual-distraction condition and five out of twelve participants in the cognitive-distraction condition experiencing one or more imminent alerts. In the timing condition, half of the visual-distraction group and one-third of the cognitive-distraction group experienced imminent alerts. Three out of eleven and three out of twelve participants experienced imminent alerts in the auditory condition for the visual- and cognitive-distraction groups respectively. Only one participant in each group experienced an imminent LDW alert in the suppress condition.

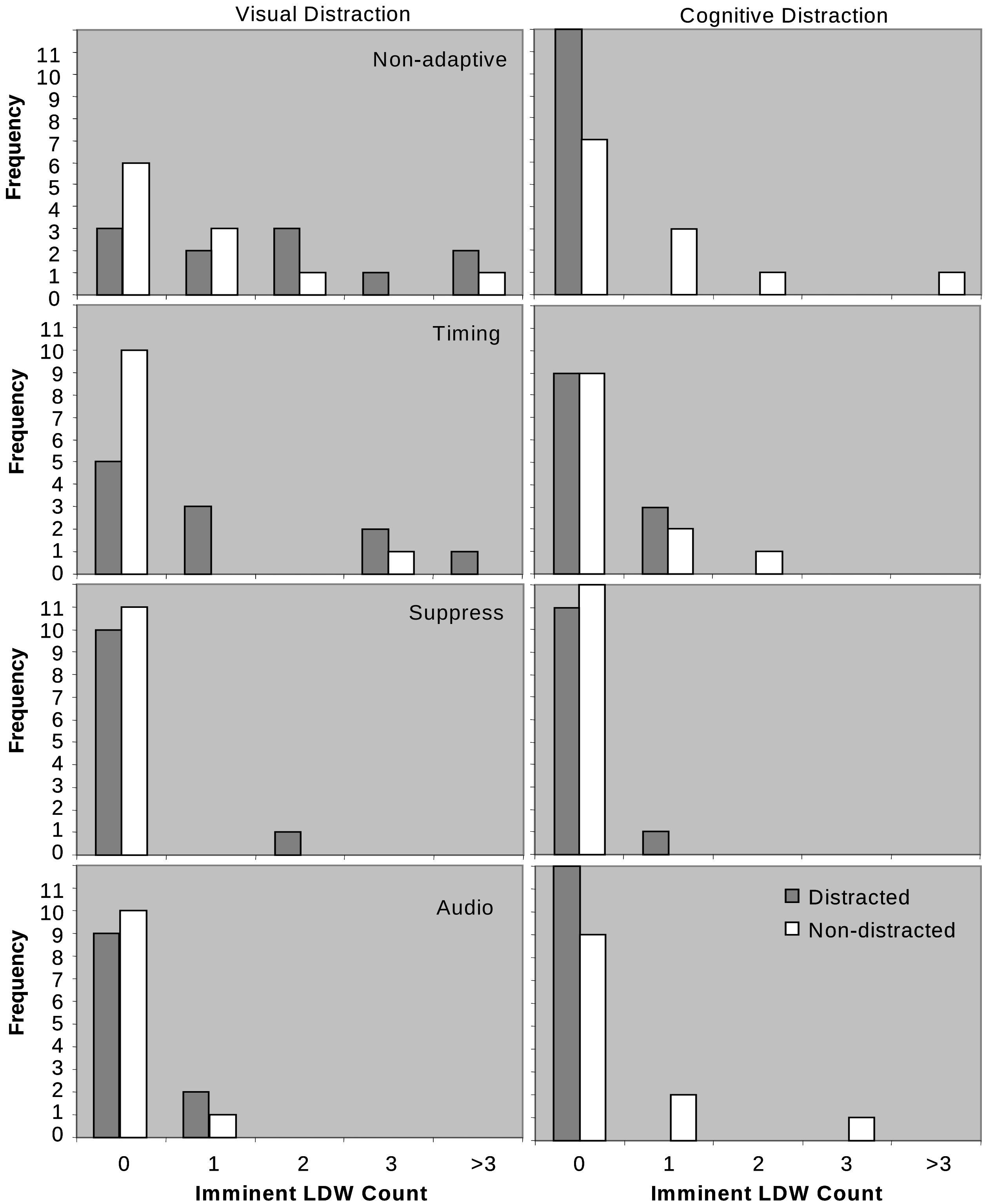

Figure 9.13. The number of participants that experienced 0, 1, 2, 3, or >3 imminent LDW Alerts as a Function of Adaptation, Distraction Presence, and Distraction Type.

9.6.2.2 Lane-keeping Performance

A 2 (***Distraction Type***) x 4 (***Adaptation***) x 2 (***Distraction Presence***) mixed ANOVA was performed on the standard deviation of lane position (SDLP) and mean absolute time-to-lane crossing (TLC). The mean absolute TLC measure averaged the values that were used to trigger LDW alerts, which were capped at 5 s. The results of these analyses are displayed in Figure 9.14.

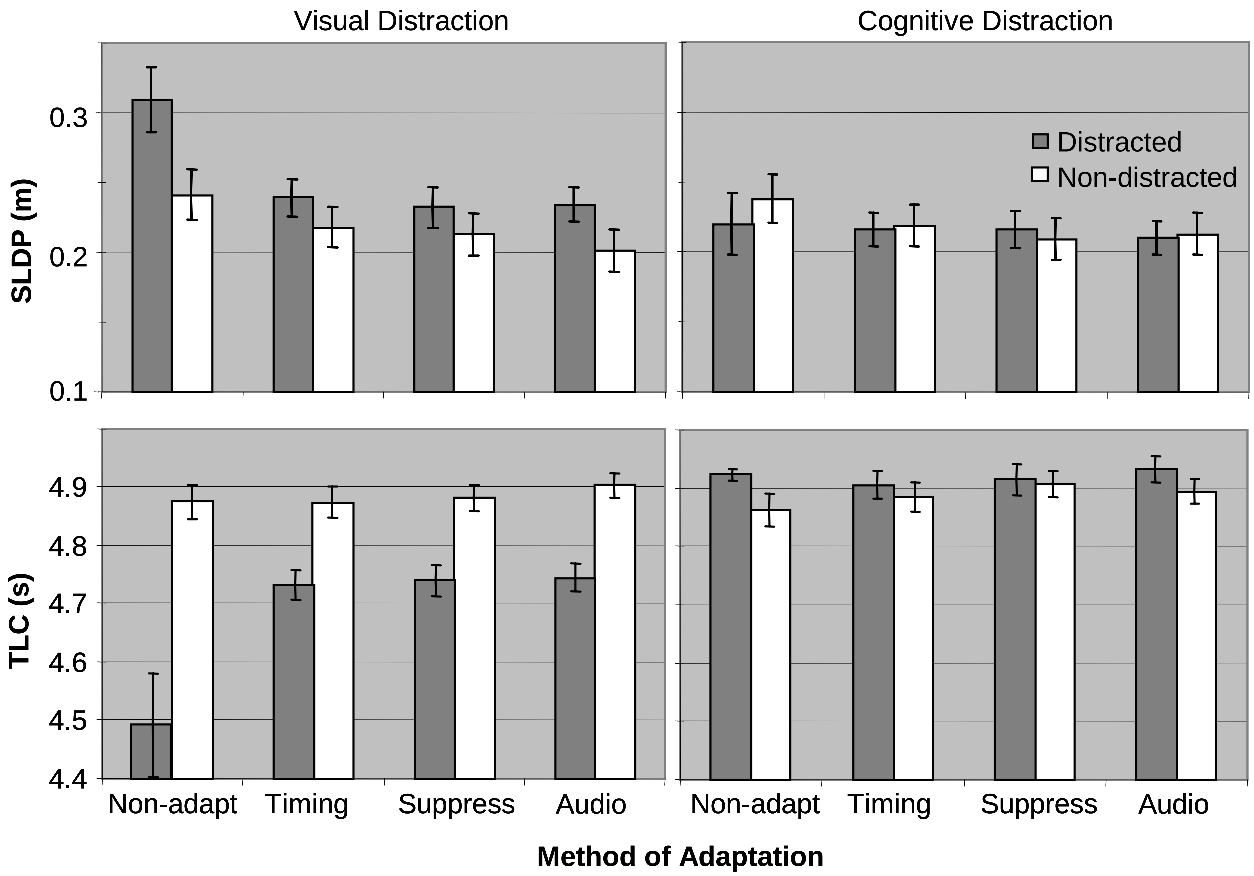

Figure 9.14. SDLP and Mean Absolute TLC as a Function of Distraction Type, Adaptation, and Distraction Presence.

Table 9.5 displays the results of the hypothesis tests. The mean absolute TLC measure was more sensitive than the SDLP measure, with mean absolute TLC revealing statistically significant differences for all interactions and main effects. The trends were similar across both variables. Post-hoc pair-wise comparisons revealed that the visual-distraction task significantly degraded TLC performance for all drives ($p < 0.001$) and significantly degraded SDLP performance for the non-adaptive and auditory drives ($p < 0.05$). The cognitive-distraction task did not significantly degrade either TLC or SDLP performance during any drives and during the non-adaptive drive participants drove with greater TLC (better lane-keeping performance) during the cognitive-distraction segments compared with the non-distraction segments ($p < 0.01$).

Table 9.5. The Results of the ANOVA Comparing the Lane-keeping Measures (SDLP and mean absolute TLC) as a Function of Distraction Type, Distraction Presence, and Adaptation.

Effect	Measure	df	F-value	p-value
Distraction Type x Adaptation x Distraction Presence	SDLP	3,63	4.84	< 0.005
	TLC		6.67	< 0.001
Distraction Type x Distraction Presence	SDLP	1,21	5.18	< 0.05
	TLC		48.05	< 0.001
Distraction Type x Adaptation	SDLP	3,63	1.84	0.15
	TLC		2.20	0.096
Distraction Presence x Adaptation	SDLP	3,63	0.85	0.47
	TLC		3.39	< 0.05
Distraction Type	SDLP	1,21	1.38	0.25
	TLC		15.16	< 0.001
Adaptation	SDLP	3,63	2.97	0.099
	TLC		13.09	< 0.001
Distraction Presence	SDLP	1,21	6.32	< 0.001
	TLC		3.49	< 0.05

During visual-distracted segments, the lane-keeping performance was worse during the non-adaptive drive compared to all other drives for both performance variables (greater SDLP and smaller TLC, $p < 0.05$). Participants exhibited significantly greater SDLP (worse lane-keeping performance) during the non-adaptive drive compared with the auditory drive ($p < 0.05$) during the non-distracted segments of the visual-distraction group. During the cognitive-distraction segments, TLC was smaller during the timing drive than the auditory drive ($p < 0.05$). During the non-distracted segments, the cognitive-distraction group exhibited worse lane-keeping performance during the non-adaptive drive compared to the suppress drive (greater SDLP and smaller TLC, $p < 0.05$).

9.6.3 Subjective Responses for the Visual-distraction Group

In order to simplify the design and because there were several missing values in the cognitive-distraction/LDW condition, the analyses were conducted on the two distraction groups separately. To make comparisons across the two types of warning system, type of ***Warning System*** was included in the analyses as an independent variable.

Figure 9.15 displays the number of participants (out of twelve) in the visual distraction group who indicated that they noticed the warning systems were adaptive as a function of adaptation and the type of warning system. There was no main effect of warning system, $\chi^2(1) = 0.49$, $p = 0.64$, however, Fishers exact tests revealed a significant effect of adaptation for both the FCW system, $\chi^2 (3) = 10.41$, $p < 0.05$, and for the LDW system, $\chi^2(3) = 12.20$, $p < 0.05$. In only the auditory condition did more than half of the participants notice that the system was adaptive. Two of the participants indicated that the FCW system seemed adaptive when it was not and one participant indicated that the LDW system seemed adaptive when it was not. Even though they were all informed that the system would not be adaptive on the first trial, participants were instructed to indicate whether the system *appeared* to be adaptive even if they knew that it was not.

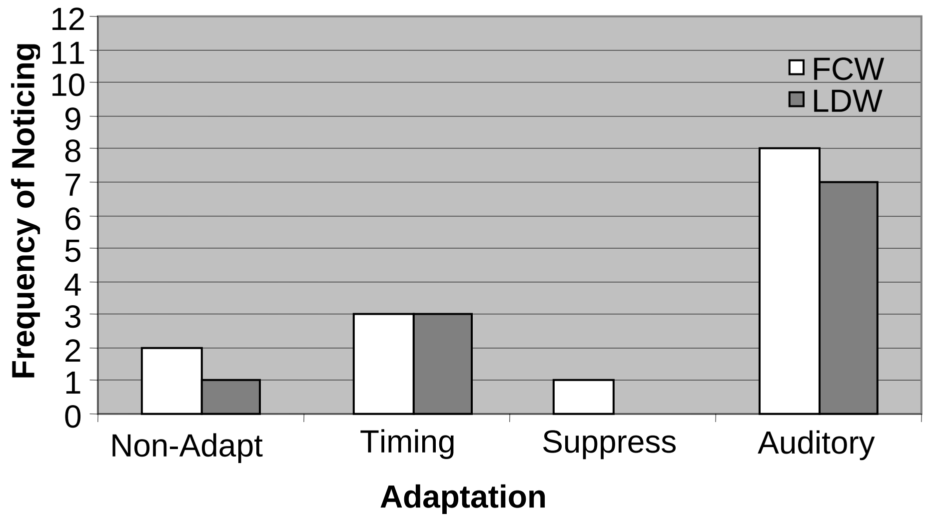

Figure 9.15. Frequency of Noticing as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Visual-Distraction Group.

Because participants only answered the adaptation-effectiveness question if they noticed that the system was adaptive, they responded to the adaptation-effectiveness question with a large number of missing values. In the FCW condition, one participant answered the adaptation-effectiveness question for the suppress adaptation and three participants answered the question for the timing adaptation. Eight (of twelve) participants responded to this question for the FCW auditory adaptation, with a mean rating of 7.25 (where 1 corresponded with “made it worse”, 5 corresponded with “no benefit”, and 9 corresponded with “extremely effective”) and responses ranging between 6 and 9. In the LDW condition, no participants responded to the adaptation-effectiveness question for the suppress adaptation, and three participants answered the question for the timing adaptation (5, 5, and 7). Seven participants responded to this question for the LDW auditory adaptation, with a mean rating of 5.43 and responses ranging between 1 and 9.

The responses to the question “…what percentage of FCW/LDW alerts seemed unnecessary” varied greatly between participants. Whereas one participant indicated percentages of 75 and 100 for the FCW and LDW systems, 54 and 60% of responses across participants were zeroes for the FCW and LDW systems respectively. The extreme nature of the responses resulted in distributions that were not amenable to an ANOVA procedure. However, a repeated-measures ANOVA procedure was conducted on the annoyance, usefulness, timing, trust, and self-confidence questions, using adaptation and warning system as independent variables.

Figure 9.16 displays participants' ratings of the system annoyance as a function of the adaptation and warning system. The type of warning system and the method of adaptation variables interacted significantly, $F(3,32) = 2.81$, $p < 0.05$. Participants' annoyance ratings were greater for the LDW system than for the FCW system, $F(1,11) = 4.70$, $p < 0.05$, and varied significantly across the adaptations, $F(3,33) = 2.66$, $p = 0.06$. Pair-wise comparisons revealed that whereas there were no significant differences within the FCW ratings, the LDW annoyance ratings were greater for the auditory condition than the non-adaptive condition, $t(32) = 3.42$, $p < 0.005$, and suppress condition, $t(32) = 3.26$, $p < 0.006$, and greater for the timing condition than the non-adaptive condition, $t(32) = 2.11$, $p < 0.05$.

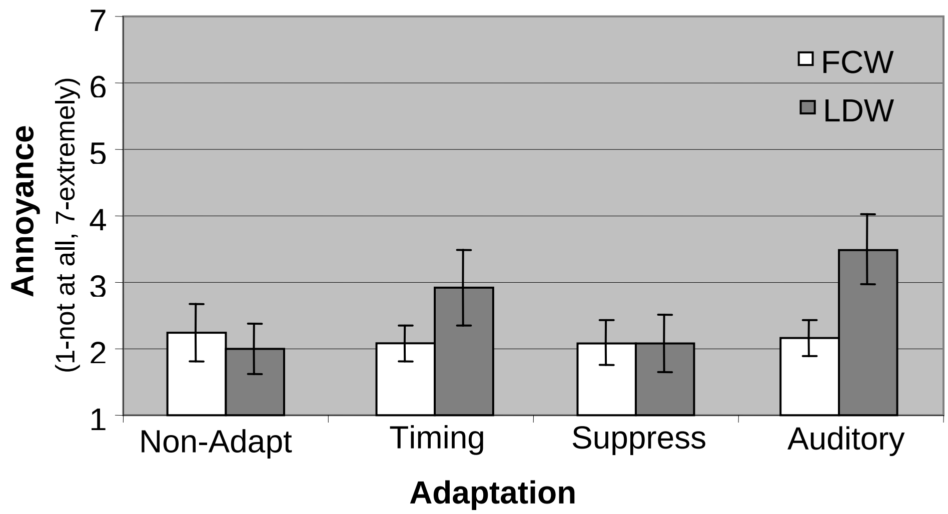

Figure 9.16. Annoyance as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Visual-Distraction Group.

Whereas the usefulness ratings did not vary significantly across methods of adaptation, the FCW system (M=5.69, SD = 1.24) was rated as more useful than the LDW system (M=4.61, SD = 2.02), $F(1,11) = 17.79$, $p < 0.005$. The timing ratings are displayed in Figure 9.17 as a function of adaptation and warning system. Timing ratings varied across the adaptation conditions, $F(3,32) = 5.17$, $p < 0.005$, and adaptation type did not interact significantly with the type of warning system. Pair-wise comparisons revealed that the auditory condition was rated as earlier than the non-adaptive, $t(32) = 3.89$, $p < 0.0005$, suppress, $t(32) = 2.38$, $p < 0.05$, and timing, $t(32) = 2.24$, $p < 0.05$, conditions.

Figure 9.18 displays the trust ratings as a function of adaptation and warning system. The trust ratings were significantly greater for the FCW system than the LDW system, $F(1,11) = 9.12$, $p < 0.05$, and also varied across adaptation conditions, $F(3,33) = 4.67$, $p < 0.01$. Pair-wise comparisons revealed that the auditory adaptation was more trusted than the non-adaptive, $t(33) = 3.04$, $p < 0.05$, and suppress, $t(33) = 3.31$, $p < 0.05$, conditions.

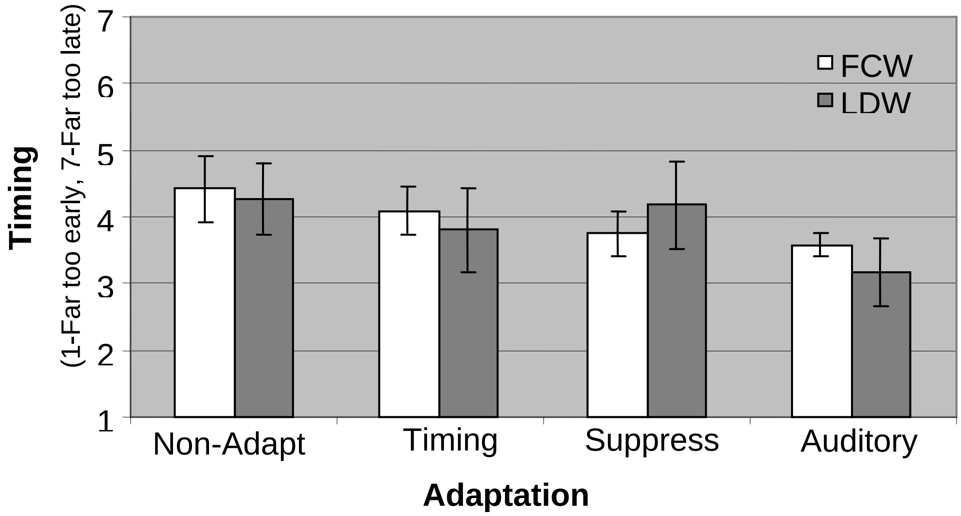

Figure 9.17. Timing as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Visual-Distraction Group.

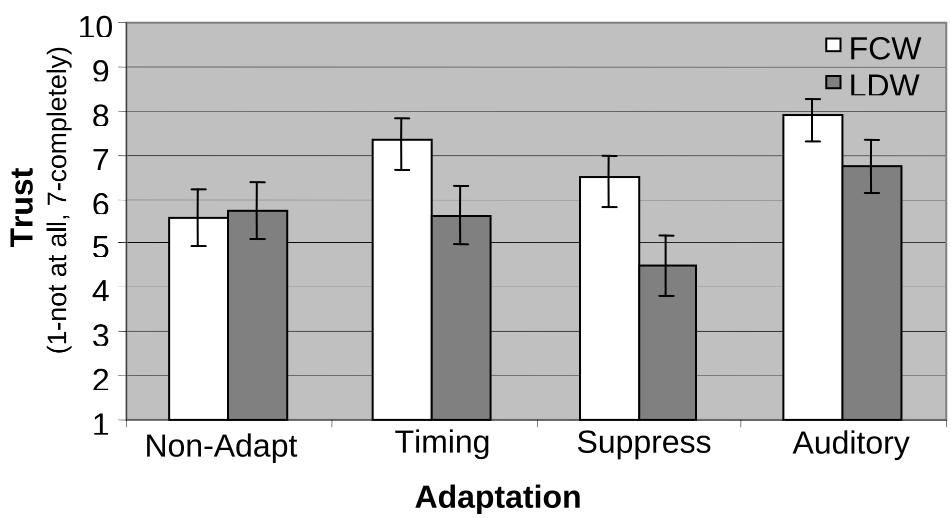

Figure 9.18. Trust as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Visual-Distraction Group.

The self-confidence ratings are displayed in Figure 9.19 as a function of adaptation type and the warning system. The effect of the warning system interacted with the type of adaptation for self-confidence ratings, $F(3,31) = 2.47$, $p = 0.08$. The timing-adapted FCW alerts produced significantly greater self-confidence ratings than the timing-adapted LDW system, $t(31) = 2.14$, $p < 0.05$, and the non-adaptive FCW system, $t(31) = 2.12$, $p < 0.05$.

Participants concluded the questionnaire by ranking their preference for the four different drives that they experienced. The results of these ranks are displayed in Figure 9.20 for the FCW and LDW systems. The preference rankings approached significance for the FCW adaptations, $\chi^2(3) = 7.50$, $p = 0.06$, but not the LDW adaptations. The auditory adaptation of the FCW system was ranked significantly lower (more preferred) than the non-adaptive FCW system ($p < 0.05$ with Nemenyi's procedure).

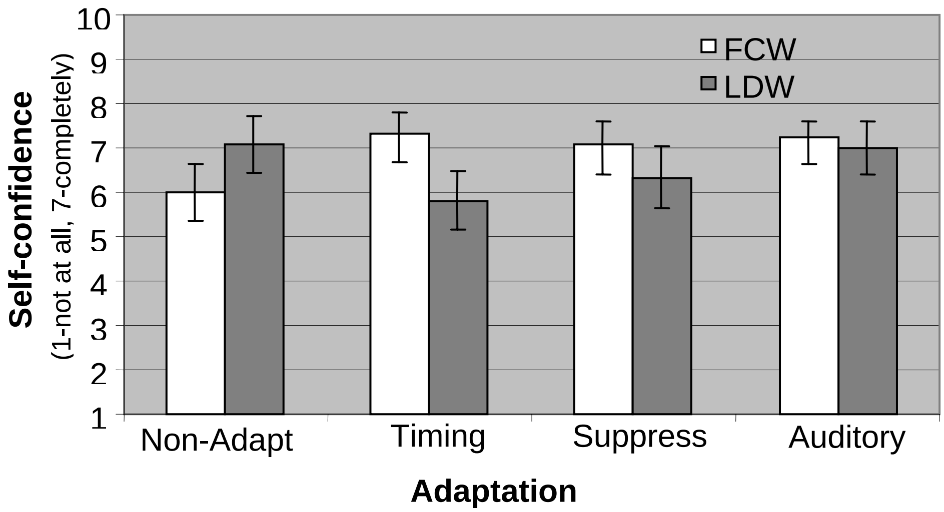

Figure 9.19. Self-confidence as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Visual-Distraction Group.

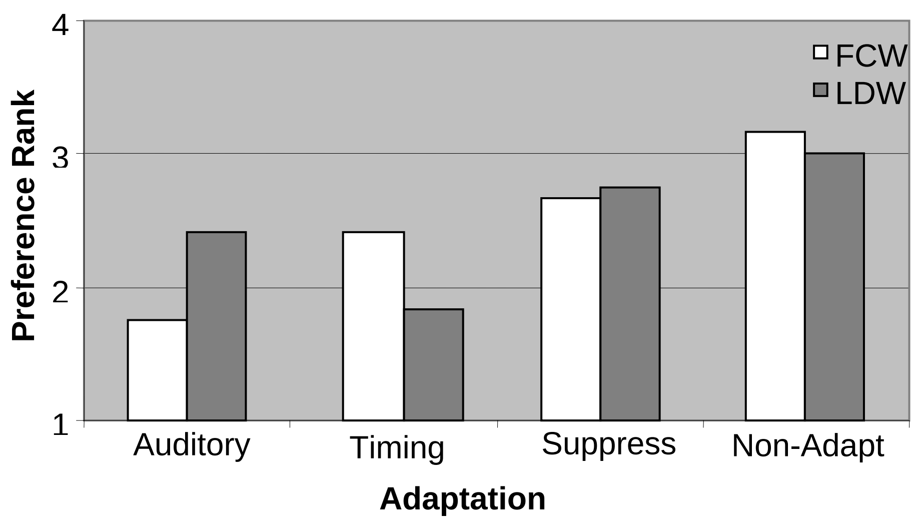

Figure 9.20. Preference Ranks as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Visual-Distraction Group.

9.6.4 Subjective Responses for the Cognitive-distraction Group

Half of the participants in the cognitive-distraction condition provided incomplete answers to the questions about the LDW system and two participants failed to answer a single question about the LDW system. These participants explained that they had received insufficient exposure to the LDW system to make an informed judgment. Because of the large number of missing values in the Cognitive-distraction/LDW system conditions, an ANOVA was conducted on only the Cognitive-distraction/FCW system data.

Figure 9.21 displays the number of participants who indicated that they noticed that the warning systems were adaptive as a function of the method of adaptation and the type of warning system. The only statistically significant difference in noticing frequencies was the difference between the FCW and LDW systems, $\chi^2(1) = 7.26$, $p < 0.05$. The participants noticed the FCW adaptations more than the LDW adaptations. Due to the large number of missing values with the LDW system, no further analyses were conducted on the LDW data set.

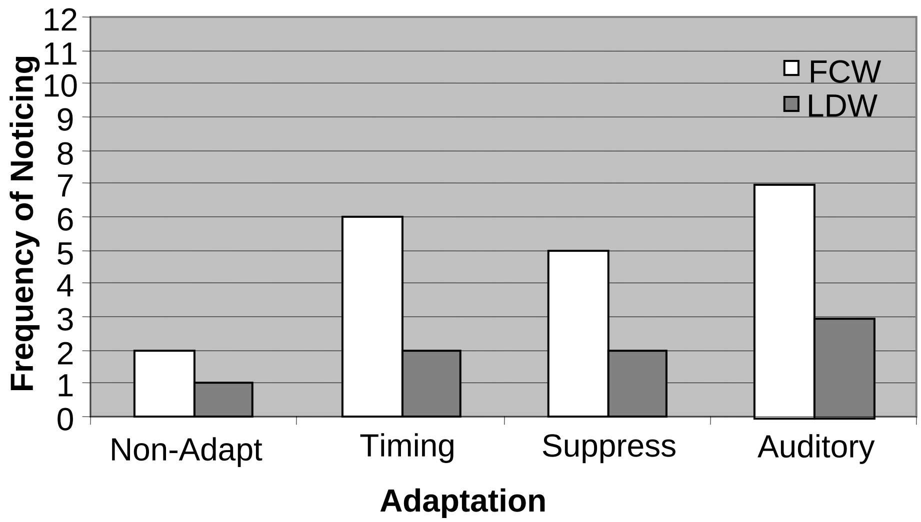

Figure 9.21. Frequency of Noticing as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Cognitive-Distraction Group.

Because participants only answered the adaptation-effectiveness question if they noticed that the system was adaptive, the suppress and timing adaptations received a large number of missing values. Seven participants answered the adaptation-effectiveness question for the auditory FCW adaptation, revealing a range of 2 to 8 and an average of 6.14 (where 1 corresponded with "made it worse", 5 corresponded with "no benefit", and 9 corresponded with "extremely effective"). Six participants answered the adaptation-effectiveness question for the timing FCW adaptation, revealing a range of 2 to 6 and an average of 4.17. Five participants answered the adaptation-effectiveness question for the suppress FCW adaptation, revealing a range of 2 to 7 and an average of 5.20.

The responses to the question "…what percentage of FCW alerts seemed unnecessary" varied greatly between participants. Whereas one participant indicated percentages of 50 for two of the FCW adaptations, 67% of responses across participants were zeroes.

Similar to the visual-distraction group's responses, the extreme nature of the responses resulted in distributions that were not amenable to an ANOVA procedure.

A repeated-measures ANOVA procedure was conducted on the cognitive-distraction group's responses to the annoyance, usefulness, timing, trust, and self-confidence questions for the FCW system. The only independent variable for this analysis was adaptation type.

Figure 9.22 displays participants' ratings of annoyance as a function of adaptation and warning system. The annoyance ratings varied significantly across adaptations for the FCW condition, $F(3,33) = 2.83$, $p = 0.05$. Pair-wise comparisons revealed that the auditory-adapted FCW system was more annoying than the non-adapted FCW system, $t(33) = 2.80$, $p < 0.01$.

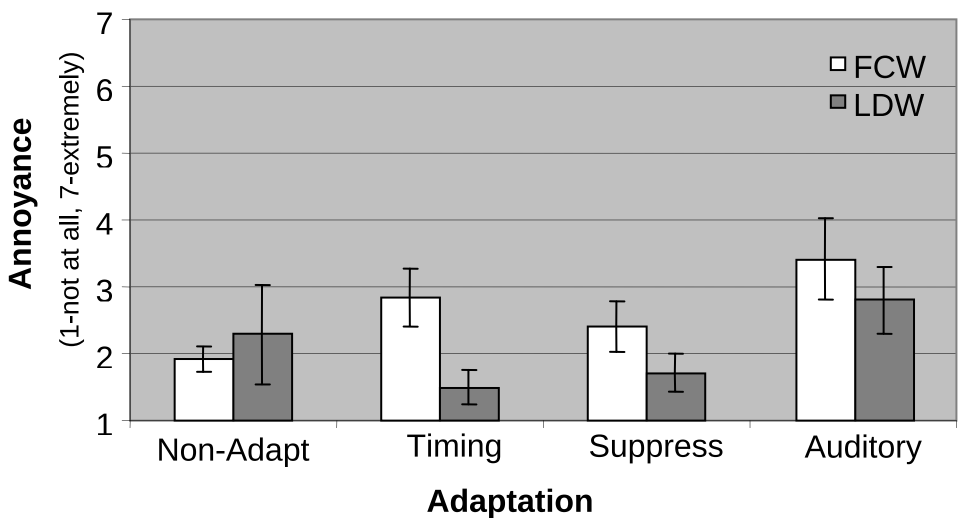

Figure 9.22. Annoyance as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Cognitive-Distraction Group.

The usefulness ratings varied significantly across the adaptations for the FCW condition, $F(3,33) = 7.51$, $p < 0.001$ (see Figure 9.23). Pair-wise comparisons revealed that the timing adaptation was considered to be less useful than the auditory, $t(33) = 3.12$, $p < 0.005$, suppress, $t(33) = 3.64$, $p < 0.001$, and Non-, $t(33) = 4.42$, $p < 0.0001$, adaptations of the FCW system.

The timing ratings are displayed in Figure 9.24 as a function of the adaptation types and warning systems. Timing ratings of the FCW system varied across the adaptation conditions, $F(3,33) = 3.08$, $p < 0.05$. Pair-wise comparisons revealed that the auditory adaptation of the FCW system was rated as earlier than the suppress adaptation, $t(33) = 2.06$, $p < 0.05$, and that the timing adaptation of the FCW system was rated as earlier than the suppress adaptations, $t(33) = 2.68$, $p < 0.05$, and non-adaptive condition, $t(33) = 2.06$, $p < 0.05$.

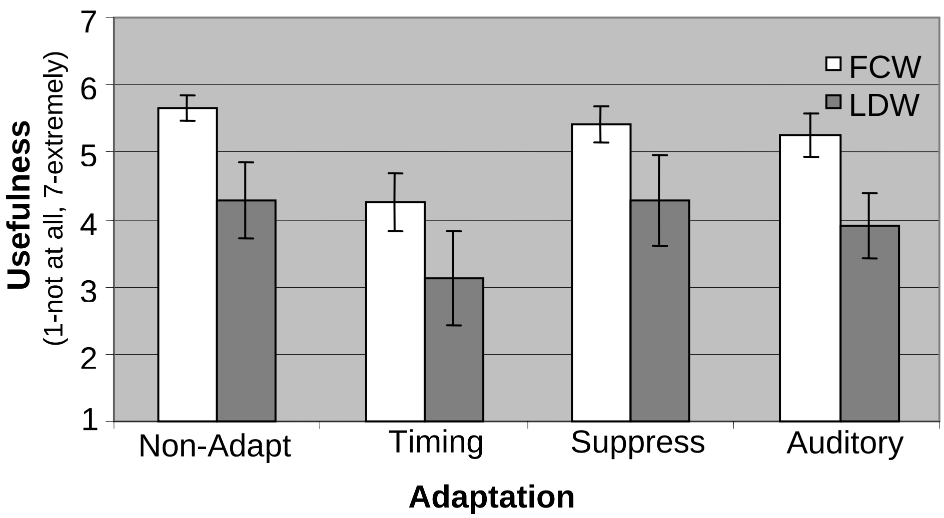

Figure 9.23. Usefulness as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Cognitive-Distraction Group.

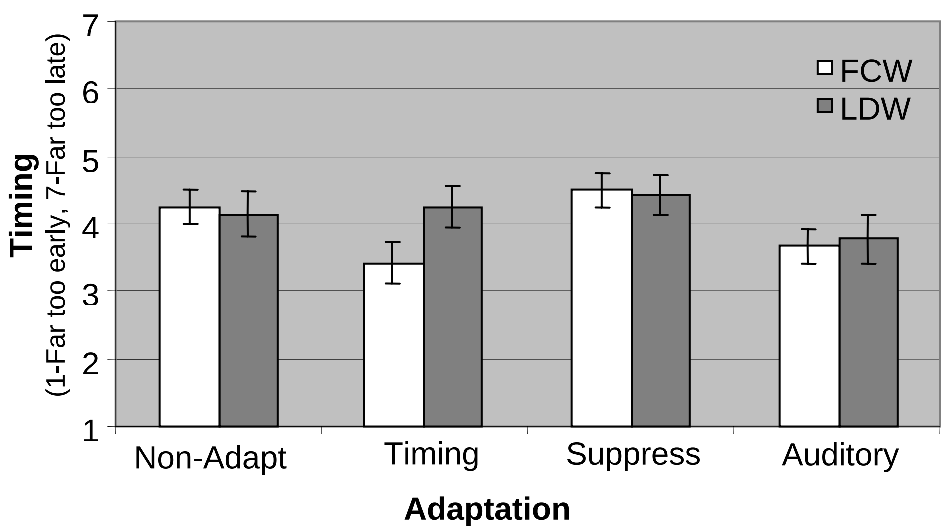

Figure 9.24. Timing as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Cognitive-Distraction Group.

The ratings for the trust and self-confidence questions did not reach statistical significance. An analysis of the preference rank did not reveal statistical significance, however, these data are displayed in Figure 9.25. Although not statistically significant, it is interesting to note that the suppress adaptation (only effecting one participant) and non-adaptive condition were the most preferable alternatives for the LDW system in the cognitive-distraction group. For the cognitive-distraction group, there is no clear preference for any of the FCW adaptations.

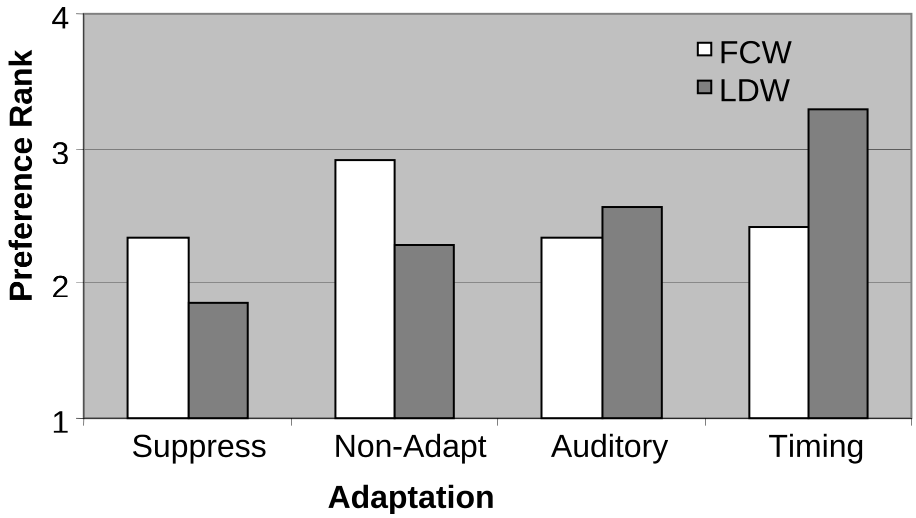

Figure 9.25. Preference Rank as a Function of Adaptation Types for the FCW and LDW Warning Systems in the Cognitive-Distraction Group.

9.7 EXPERIMENT 2 DISCUSSION

Driving performance that was measured by response-time and lane-keeping parameters tended to be poorer during the non-adaptive drive than the three drives with adaptive systems. However, this effect cannot necessarily be attributed to the success of the adaptations because the non-adaptive drive was confounded with the order effect. Whereas the order of presentation of the adaptive systems was counterbalanced across the last three drives, participants invariably experienced the non-adaptive drive during the first drive. This manipulation was selected to provide participants with a basis of comparison for judging the effectiveness of the subsequent adaptations.

There are at least two hypotheses that would predict poorer performance on the first drive. One hypothesis is the learning effect, suggesting the drivers may become more effective at time-sharing the secondary and driving tasks with increased practice. The lane-keeping performance of drivers during the visual-distraction segments is significantly worse during the first trial (non-adaptive) than during the other three trials. Another hypothesis is that participants may have been more inclined to experiment with the warning system during the first drive, producing lane-deviations and waiting to brake more than during the subsequent drives. Because participants may be more likely to experiment with the systems when they are not occupied with a secondary task, this hypothesis may in part account for the significantly poorer lane-keeping performance that was observed during the non-distracted segments of the cognitive group's first drive. The result of the order confound may be that comparisons between driving performance during the adaptive and non-adaptive drives may be misleading. Comparisons between driving performance in the adaptive drives (where the order was counterbalanced) are more likely to be valid.

Another weakness of this study is that the FCW and LDW systems were programmed to behave more reliably than what would be possible on real roadways with the current state-of-the-art systems. In the driving-simulator there were no sensor errors and the simplistic driving scenarios did not involve more complicated events such as closing in on a turning vehicle. Due to the increased complexity and sensor requirements of driving in reality, it is likely that false and nuisance alerts would have occurred that did not occur in this simulation. In reality, these adaptations could provide an additional means of suppressing nuisance alerts when the driver is better able to evaluate and address the driving situation. This may be especially true of the suppress adaptation, which provides the most extreme adaptive response to imminent alerts when the driver is attentive. Therefore, it may be likely that the effects of these adaptations have been underestimated by the perfect performance of the virtual environmental "sensors".

Table 9.6 summarizes the advantages and disadvantages of the different adaptations relative to each other as a function of the response times and the subjective criteria. Only the results associated with statistically significant pair-wise comparisons are displayed in this table.

Table 9.6. Summary of the Advantages (+) and Disadvantages (-) of the Three Types of Adaptation as a Function of Distraction Type and Performance and Subjective Criteria

	Visual-distraction			Cognitive-distraction		
	Timing	Suppress	Auditory	Timing	Suppress	Auditory
ART or BRT -3 (distracted)	**+**	**-**		**+**		
ART or BRT -5 (distracted)				**+**		
ART or BRT -3 (non-distracted)	**-**					
ART or BRT -5 (non-distracted)	**-**				**-**	
Annoyance	**-**(LDW)		**-**(LDW)			**-**(FCW)
Usefulness				**-**(FCW)		
Timing			**-**	**-**(FCW)		**-**(FCW)
Trust			**+**			
Preference			**+**(FCW)			

Note. The advantages (+) and disadvantages (-) represent analyses where there is a significant difference between the adaptation and at least one other type of adaptation (including non-adaptation).

9.7.1 Timing Adaptation

The timing adaptation not only changed the timing of many of the FCW and LDW alerts, but also changed the number of alerts that drivers received. Despite this influence, the timing adaptation seemed to go relatively unnoticed. Only one quarter of the drivers in the visual-distraction group claimed that they noticed the FCW and LDW adaptations. Perhaps this can be explained because these participants were distracted during the half of the drive that the timing effect would have been most salient. The time-sharing of the visual-distraction task may have made it difficult to notice the timing changes, especially to the cautionary alerts, which had no auditory stimulus. In the cognitive-distraction group half of the participants noticed the FCW timing-adaptation and only two of the twelve participants claimed that they noticed the LDW timing-adaptation.

Compared with the other methods of adaptation, the timing adaptation had a large effect on the driver response times. During the distraction segments, participants responded significantly faster to the -3 m/s^2 braking events during the Timing drive than in the other drives. The visual-distraction group also exhibited smaller response times in response to the -5 m/s^2 braking events during the distraction segments of the timing drive compared to the distraction segments of the auditory drive. This effect occurred in the opposite direction for the visual distraction group during the non-distraction segments. These participants responded significantly slower during the timing drive than in the suppress and auditory drives.

Within the timing drive, participants responded significantly earlier during the distraction segments[9] than in the non-distraction segments. The most likely explanation for these

[9] The significant differences were exhibited in the visual-distraction group ART values for the -3 m/s^2 and -5 m/s^2 braking events and the BRT values for -3 m/s^2 braking events. They were also exhibited in the cognitive-distraction group for the ART and BRT values in response to the -3 m/s^2 braking events.

effects is that the earlier and more frequent FCW alerts reversed the typical effect of the distraction task slowing response times. The 2-s difference in timing between the distracted and non-distracted segments appears to have over-compensated for the effect of distraction on response times, and therefore may have been excessive.

Like the three other FCW systems, the visual-distraction group rated the timing-adapted FCW system as not annoying (approximately 2 on a seven-point scale). They rated the timing-adapted FCW system as being numerically[10] the least annoying, timing closest to "just right", inspiring the greatest self-confidence, and the second most preferred alternative. The cognitive-distraction group did not rate the timing-adapted FCW system as favorably. When numerically compared to the other three FCW systems, the cognitive-distraction group rated the timing-adapted FCW system as being the earliest timing (significantly earlier than the suppress adaptation), least useful, least trusted, second-most annoying, and inspiring the least self-confidence. Although many of these results did not reach statistical significance, the consistent direction of these data may suggest that adapting the timing of the FCW system to the driver's state of cognitive distraction may not be well received. Perhaps the magnitude of the timing change between distraction conditions may have been excessive given the small effect that cognitive distraction had on the response times.

Although the timing adaptation affected the timing and occurrences of the LDW system, there was no measurable effect on lane-keeping-related performance (average absolute TLC and SDLP) compared with the other two adaptive systems. Participants in the visual-distraction group rated the timing-adapted LDW system as significantly more annoying than the non-adapted LDW system. The increase in the sensitivity of the LDW system that led to an average of 17 additional cautionary alerts per driver and additional imminent alerts for five of the eleven drivers is likely to have increased the annoyance of the timing adaptation. Despite the increased annoyance and the fact that the timing-adapted LDW system was rated as being the least useful, the visual-distraction group rated the timing adaptation as being the most preferred LDW alternative. The opposite occurred in the cognitive-distraction group, with the timing adaptation being rated as the least preferred LDW alternative.

9.7.2 Suppress Adaptation

The effects of the Suppress adaptation were quite subtle. In the two groups only six (out of 24) participants claimed to notice the adaptation to the FCW system and only two participants noticed the adaptation to the LDW system. By design, this adaptation suppressed all 69 FCW alerts that would have otherwise occurred during the non-distracted segments of the two groups. The Suppress adaptation had a smaller effect on the LDW system, suppressing only one imminent LDW alerts for four out of 24 drivers that would have otherwise occurred during the non-distracted segments. Perhaps the subtlety of the suppress adaptation can be explained by drivers requiring fewer alerts when they were attentive. In the absence of distraction, there was little

[10] The differences did not necessarily reach statistical significance.

reason for drivers to drift out of their lane and thus little reason for an alert (that would have been suppressed) to occur. When the lead vehicle began braking, in many cases attentive drivers may have responded before the alert criterion was reached. This would lead to few alerts that were available for the adaptation to suppress. However, for the -5 m/s^2 braking events, the suppression of imminent alerts did appear to slow the driver's responses, with drivers in both groups braking later in the non-distracted segments than in the distracted segments. Figure 9.11 displayed that this effect was quite pronounced for the cognitive-distraction group (a difference of over 300 ms). It is difficult to explain why the cognitive-distraction group was so much later to respond to the -5 m/s^2 braking events during the non-distracted segments than the visual-distraction group. This effect is quite peculiar because when a driver is not distracted, the type of distraction that is not being received seems unlikely to have an effect. Perhaps when the drivers were cognitively saturated, they were distracted from noticing the way that the system responded differently between the different distracted vs. not-distracted segments.

During the segments of non-distraction, the visual-distraction group released the accelerator earlier and braked earlier to the -5 m/s^2 events during the suppress drive than during the timing drive. This may support McGehee and Brown's (1998; cited in Lee, McGehee, Brown, and Reyes, 2000) observation that a late warning may actually slow driver responses more than no warning at all. However, during the segments of non-distraction, the cognitive-distraction group responded later during the Suppress drive than any of the other drives.

The subjective ratings of the FCW and LDW systems during the suppress drive tended to reflect the fact that few participants noticed the suppress adaptation. Compared to the other two drives, the FCW and LDW systems during the suppress drive were rated as least useful, least trusted, least inspiring of self-confidence, and least preferred by the visual-distraction group. The only positive signs were that the visual-distraction group gave the suppress FCW system intermediate ratings of annoyance and timing and rated the suppress LDW system as being the least annoying and having the best timing compared with the other two adaptation drives. The cognitive-distraction group rated the suppress FCW system as being the least annoying, most useful, and most trusted alternative compared with the other two types of adaptation. However, the cognitive-distraction group rated the timing as being later than "just-right", probably reflecting the slower reaction times in the -5m/s^2 braking events during the non-distracted segments.

9.7.3 Auditory Adaptation

The 24 participants of the combined two groups received an average of 4.5 cautionary FCW alerts each during the distracted-segments of the auditory drive. The auditory adaptation provided a voice message during these cautionary alerts, informing the driver of the "vehicle braking". During the non-distracted segments of the auditory drive, participants also received an average of 2.7 "silent" imminent FCW alerts, where no auditory stimulus accompanied the alert. On average, the visual-distraction participants experienced 8.3 cautionary LDW alerts during the distracted segments of the auditory drive, hearing the voice message of either “drifting left” or “drifting right”. The cognitive-distraction group participants received fewer cautionary LDW alerts during the distracted segments, averaging only 1.5 alerts per participant. Because attentive drivers have little reason to drift out of the lane, the “silent” imminent LDW alerts were relatively rare in both groups. Only one participant in the visual-distraction group experienced one “silent” imminent LDW alert. Two participants in the cognitive-distraction group experienced one “silent” imminent LDW alert and one participant experienced three.

The auditory adaptation was the most noticeable adaptation that participants experienced. It was the only method of adaptation that more than half of the participants in each group noticed. This is likely to have resulted from the voice messages that accompanied the cautionary alerts being more salient than the other forms of adaptation.

During segments of distraction, participants revealed shorter BRT values in response to the -3 m/s^2 braking events during the auditory drive than the suppress drive. However, accompanying the cautionary FCW alerts with the voice message (auditory adaptation) was not as effective at expediting the driver responses to the -5 m/s^2 braking events as having a more immediate imminent alert (timing adaptation). During segments of non-distraction, removing the audible component of the imminent FCW alerts (auditory adaptation) delayed driver responses less than delaying the imminent alert (timing adaptation). Removing the auditory stimulus from the warnings did not appear to degrade the attentive driving performance. If this result is valid on real roadways, it may suggest a promising way of reducing annoyance without sacrificing the benefit of potentially useful alerts.

Participants in the visual-distraction group rated the FCW system in the Auditory drive as the most preferred, most trusted, and most useful. On the less desirable side, this system was rated as the most annoying and as having the earliest timing, probably reflecting the fact that the voice message accompanied the cautionary alert level. Participants in the cognitive-distraction group also rated the FCW system in the auditory drive as the most preferred but most annoying alternative.

The LDW system in the auditory drive shared similar undesirable characteristics (annoyance and earliest timing) as the FCW system, however, unlike the FCW system, the auditory-adapted LDW system was not the most preferred alternative of the visual-distraction group.

9.7.4 Adapting to Visual- vs. Cognitive-distraction Tasks

Figure 9.26 displays the driver’s feedback for the effectiveness, annoyance, usefulness, and trust ratings averaged over the three FCW-adaptation methods for the visual and cognitive groups. In comparing the ratings of the visual-distraction group with those of the cognitive-distraction group, the visual-distraction group rated the pooled FCW adaptations as significantly more effective ($p < 0.005$), less annoying ($p < 0.05$), more trusted ($p < 0.05$), and more useful ($p < 0.005$) than the cognitive-distraction group. This result suggests that adapting FCW to visual-distraction is significantly more effective than adapting FCW to cognitive-distraction. This observation is mirrored by the fact that participants in the cognitive-distraction group exhibited no clear preference for any type of adaptation. Although it was not statistically significant, the cognitive-distraction group rated the non-adaptive FCW system as being the least annoying and most useful when compared with the three adaptive alternatives. Considering these results as a whole, there is little evidence in this study to suggest that the cognitive adaptations used in this study were beneficial to the driver in any way. If adapting alerts to the driver's cognitive state can be advantageous, it is likely that these adaptations need to be more subtle than those used in this study.

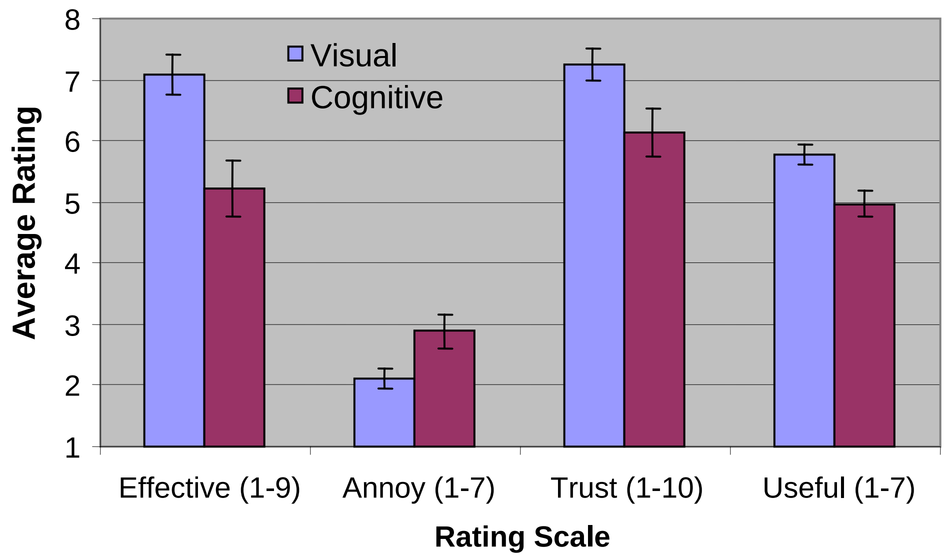

Figure 9.26. Participant responses to the effectiveness, annoying, trust, and usefulness scales averaged over the three adaptive drives (timing, suppress, auditory) as a function of distraction type.

Adapting the LDW system to cognitive distraction did not appear to be an effective strategy either. The cognitive-distraction task did not degrade lane-keeping performance and so drivers in the cognitive-distraction group received few LDW alerts. This result is consistent with the results of the Horrey and Wickens (2004) meta-analysis that found little degradation of lane-keeping performance as a result of cell phone conversations. This experiment did not support the hypothesis that an LDW alert is more likely to be useful when the driver is distracted by a purely cognitive task. Instead these data appear to suggest that LDW systems should only adapt to the driver's state of visual distraction.

9.8 CONCLUSIONS

The two experiments of this task provide varied support for the strategy of adapting countermeasures to the driver's state of distraction. Whereas the adaptations to visual distractions tended to support more desirable ratings, adaptations to cognitive distractions did not. Experiment 2 suggested that an adaptive FCW system may be able to counteract the delays of driver distraction in some circumstances and increase driver acceptance of the alerts.

In most circumstances of Experiment 2, the annoyance ratings were relatively low. However, drivers who are exposed to a real FCW and LDW system on public roadways may be more likely to experience the annoyance of inappropriate alarm activations and may therefore better appreciate a system that is capable of reducing nuisance alerts. Unlike real roadways, in the driving simulator the driver only received in-path FCW alerts, and the performance of the two warning systems was far superior to that which can be expected of real systems in the near future. Furthermore, observations of the ACAS FOT suggest that drivers become increasingly intolerant of nuisance alerts as they experience the system for longer durations. Because the suppress-adaptation provides an additional method for reducing the rate of nuisance alerts, the experimental method used in this study may have particularly underestimated the benefit of the suppress adaptation. Despite the relatively negative results of the suppress adaptation exhibited in this driving-simulator experiment, on real roadways suppressing alerts may still be useful for counteracting the potential annoyance of inappropriate LDW activations (e.g., changing-lanes and intentional lane deviations). The work of Summala, Nieminen, and Punto (1996) suggests that experienced drivers are able to perform lane-keeping using only peripheral vision, and this may provide support for the adaptation of suppressing LDW alerts based on relatively gross measures of whether the driver's eyes (or even head) are oriented to the forward roadway.

The results of Experiment 2 may suggest that a combination of adaptation strategies may be more effective than any one of the adaptation strategies alone. For example, providing earlier FCW timing for distracted drivers appeared to be beneficial, however, providing late FCW alerts for attentive drivers in some cases was worse than providing no alert at all. McGehee and Brown (1998; cited in Lee, McGehee, Brown, and Reyes, 2000) argued that late warnings may actually delay drivers' responses more than providing no warning at all. Likewise, suppressing the auditory component of imminent alerts appears to be a promising strategy for reducing annoyance without reducing warning effectiveness, however, providing the voice warnings during cautionary alerts is likely to be overly annoying on real roadways. Therefore, combining a timing strategy for distracted drivers (earlier warnings) with an auditory strategy for attentive drivers (suppress the auditory) may be a more effective alternative than a timing or auditory adaptation alone. Tijerina (1999) revealed that drivers rarely glance away unless the range rate is closer to zero, suggesting that when drivers look away while the FCW system detects significant closing on a lead vehicle, they may be unaware of the developing situation. Combinations, such as using longer expected reaction times for distracted drivers and suppressing auditory stimuli for attentive drivers, can be evaluated in the second phase of the SAVE-IT program.

9.8.1 Human Factors Guidelines

At this preliminary stage of research, it is too early to make informed guidelines for the design of adaptive safety warning countermeasures. However, some suggestions can be offered that may form the basis of some tentative recommendations for future practices. Those suggestions would be as follow:

1. *Safety warning countermeasures should adapt more to visual distraction than to cognitive distraction. Because lane-keeping performance seems to be more tightly coupled to the driver's visual rather than cognitive behavior, LDW systems should adapt only to visual and not to cognitive distraction.*

2. *Voice stimuli should be used sparingly to alert the driver and even when they accompany the cautionary stage, voice stimuli do not appear to significantly expedite the driver's reaction to the alert. Voice stimuli appear to annoy the driver more than tonal stimuli.*

3. *Providing earlier warnings for distracted drivers (timing adaptation) appears to be an effective means of counteracting the delaying effects of visual distraction. The strategy of delaying warnings for attentive drivers should be implemented with caution because it appears that late warnings may actually slow the driver's response compared with no warning at all. The 2-s difference between distracted and non-distracted alerts that was used in this study appears to be excessive, especially for cognitive-distraction.*

9.8.2 Phase II Planning

Experiment 1 suggested that the effects of driver expectation might be at least as great in magnitude as the effects of driver distraction. One hypothesis could be that these expectation effects are an artifact of the driving-simulator environment (e.g., poor perception of optic flow). Research is required to further investigate this possibility. If the large effects of expectation are not a simulator-related artifact and do represent a real phenomenon, then if they can accurately be measured, driver expectations may provide another important source of information for adaptive warning systems. The results of Experiment 1 in combination with observations from the Smith (2002) study suggest that the speed variability of the lead-vehicle may predict driver expectations. When the lead-vehicle maintains a constant speed for long periods of time, the driver may become desensitized to the lead vehicle and an adaptive system might predict longer reaction times. When a lead-vehicle has exhibited constant changes in speed (for example, in heavy traffic or near an intersection) the driver of the host vehicle is more likely to be receptive to future changes in the state of the lead vehicle. The range to the lead vehicle also appears to be an important variable for predicting driver reaction times. A study that examines the potential interactions between driver distraction, headway, and lead-vehicle speed variability could provide useful information for the SAVE-IT program. Due to the potential issues of driving-simulator artifacts, conducting this research using a real host vehicle and a surrogate lead vehicle (see Figure 9.27) on a test track may be the most effective research strategy.

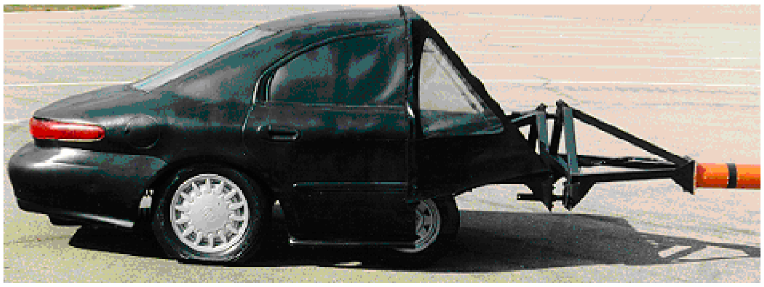

Figure 9.27. A surrogate target used the CAMP Forward Collision Warning during test-track research. A surrogate target appears similar to a real vehicle from the rear view but can sustain a low-speed impact without damage to either vehicle.

The tentative nature of the proposed recommendations reveals that the Safety Warning Countermeasures Task is not complete in Phase I. Many important questions require satisfactory answers before the evaluation in Phase II commences. Perhaps the most important question involves the possibility of combining adaptation strategies and the interaction between the adaptive countermeasures and inappropriate alert activations. More research is required in these two areas. In order to gain insight into these questions, it seems that these systems must be evaluated on public roadways, where the countermeasure systems are exposed to the complexity and uncertainty of real driving conditions. Assessing the system performance on public roadways will afford a deeper analysis of the interaction between the adaptation strategies and the presence of inappropriate alert activations.

Another area for further exploration is the use of intent-detection information. Experiment 2 used simple scenarios where driver intent information was not relevant. However, in naturalistic driving situations, drivers execute maneuvers such as changing lanes that may trigger nuisance alerts in non-adaptive warning systems. For example, changing lanes could trigger an LDW warning as the driver intentionally drifts out of the lane and could trigger an FCW warning if the driver closes in quickly on a lead vehicle as the host vehicle changes lanes. Exploring the effects of adapting warning systems to intent information may provide useful information for Phase II of the SAVE-IT program.

To achieve these research objectives, it is suggested that an instrumented vehicle be distributed among commuters to collect naturalistic driving data while the vehicle presents the driver with different adaptive countermeasure strategies. Commuters could use the vehicle for their commute to and from work on a weekly basis. Each of the round trips could present the drivers with a different countermeasure strategy and the drivers could complete a questionnaire after each round trip. The data that is collected could be used after it is collected to run different algorithms that may be tuned on an iterative basis. Using driver's commutes may provide a more naturalistic evaluation of typical driver behavior and driver acceptance issues.

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APPENDIX A: PAIR-WISE COMPARISONS BETWEEN DRIVER REACTION TIMES

Table 9.A1 reveals the combinations of Distraction Type, Adaptation, and Deceleration Rate in which the presence of a distraction task significantly affected the ART and BRT response ($p < 0.05$).

Table 9.A1. Statistically Significant Pairwise Comparisons of Distracted vs. Non-distracted Response Times as a Function of Distraction Type, Adaptation, Deceleration Rate and Response Type

<table>
<tr><th></th><th>Distraction Type</th><th>Adaptation</th><th>Deceleration Rate</th><th>Response Type</th></tr>
<tr><td rowspan="6">Distracted Response Later than Non-Distracted Response</td><td rowspan="5">Visual</td><td>Non-adaptive</td><td>$-3\ m/s^2$</td><td>ART</td></tr>
<tr><td rowspan="2">Suppress</td><td>$-3\ m/s^2$</td><td>ART and BRT</td></tr>
<tr><td>$-5\ m/s^2$</td><td>ART</td></tr>
<tr><td>Auditory</td><td>$-3\ m/s^2$ and $-5\ m/s^2$</td><td>ART</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Cognitive</td><td>Auditory</td><td>$-5\ m/s^2$</td><td>ART</td></tr>
<tr><td rowspan="5">Non-Distracted Response Later than Distracted Response</td><td rowspan="3">Visual</td><td rowspan="2">Timing</td><td>$-3\ m/s^2$ and $-5\ m/s^2$</td><td>ART</td></tr>
<tr><td>$-3\ m/s^2$</td><td>BRT</td></tr>
<tr><td>Suppress</td><td>$-5\ m/s^2$</td><td>BRT</td></tr>
<tr><td rowspan="2">Cognitive</td><td>Timing</td><td>$-3\ m/s^2$</td><td>ART and BRT</td></tr>
<tr><td>Suppress</td><td>$-5\ m/s^2$</td><td>BRT</td></tr>
</table>

Note. An alpha-level of 0.05 was adopted for this exploratory analysis.

In order to further examine the effects of the different adaptations on driver response time, post-hoc pairwise comparisons (2-tailed) were. Tables 9.A2 and 9.A3 display the statistically significant differences between different types of adaptations during the distracted and non-distracted segments respectively ($p < 0.05$).

Table 9.A2. Statistically Significant Pairwise Comparisons of Response Times During the Distracted Segments for the Different Methods of Adaptation as a Function of Distraction Type, Deceleration Rate, and Response Type.

<table>
<tr><th colspan="5">During Distracted Segments</th></tr>
<tr><td rowspan="4">Timing earlier than:</td><td>All</td><td>Visual & Cognitive</td><td>$-3\ m/s^2$</td><td>ART & BRT</td></tr>
<tr><td>Auditory</td><td>Visual</td><td>$-5\ m/s^2$</td><td>BRT</td></tr>
<tr><td>Auditory</td><td>Cognitive</td><td>$-5\ m/s^2$</td><td>ART</td></tr>
<tr><td>Non-adaptive</td><td>Visual</td><td>$-5\ m/s^2$</td><td>BRT</td></tr>
<tr><td rowspan="2">Auditory earlier than:</td><td>Suppress</td><td>Visual</td><td>$-3\ m/s^2$</td><td>BRT</td></tr>
<tr><td>Non-adaptive</td><td>Cognitive</td><td>$-3\ m/s^2$</td><td>BRT</td></tr>
<tr><td rowspan="3">Suppress earlier than:</td><td>Auditory</td><td>Visual</td><td>$-5\ m/s^2$</td><td>BRT</td></tr>
<tr><td>Non-adaptive</td><td>Visual</td><td>$-5\ m/s^2$</td><td>ART</td></tr>
<tr><td>Non-adaptive</td><td>Cognitive</td><td>$-3\ m/s^2$</td><td>ART</td></tr>
</table>

Note. An alpha-level of 0.05 was adopted for this exploratory analysis.

Table 9.A3. Statistically Significant Pairwise Comparisons of Response Times During the Non-distracted Segments for the Different Methods of Adaptation as a Function of Distraction Type, Deceleration Rate, and Response Type.

During Non-distracted Segments				
Timing earlier than:	Suppress	Visual	-3 m/s^2	ART & BRT
	Suppress	Visual	-5 m/s^2	ART
	Auditory	Visual	-3 m/s^2	ART & BRT
	Auditory	Visual	-5 m/s^2	ART
Auditory earlier than:	All	Cognitive	-5 m/s^2	BRT
Suppress earlier than:	Suppress	Visual	-3 m/s^2	BRT
	Auditory	Cognitive	-3 m/s^2	BRT
	Auditory	Cognitive	-5 m/s^2	ART

Note. An alpha-level of 0.05 was adopted for this exploratory analysis.