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Final Report

Effects of Vision Enhancement Systems (VES) on Older Drivers' Ability to Drive Safely at Night and in Inclement Weather

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This report presents a human-factor analysis of the visual properties of an actual in-vehicle head-up display (HUD) system used for the Highway 7 project. The HUD system is intended to improve driving performance in conditions of limited visibility.

The HUD system projects lines that correspond to the sides and center line of the roadway onto the windshield of the vehicle, thus aiding the driver in times of low visibility. The author found that the simple, monochromatic image avoided many problems associated with other more complicated HUD designs and that the use of conformal imagery (projecting the image over the actual view) enhanced the effectiveness of the system.

This analysis complements the analysis of simulated in-vehicle head-up display done by Caird, Horrey, Chugh, and Edwards. Their report, "The Effects of Conformal and Non-Conformal Vision Enhancement Systems on Older Driver Performance," is included as an appendix to this report.

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Effects of Vision Enhancement Systems (VES) on Older Drivers' Ability to Drive Safely at Night and in Inclement Weather — Visual Human Factors Analysis of In-Vehicle Head Up Display (HUD)

Final Report

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EXECUTIVE SUMMARY

This report represents the deliverable for Tasks 5 and 7 for the subject project, which specify that a human factors (HF) analysis of the visual properties of the in-vehicle head-up display (HUD) system used for the Mn/DOT-funded Highway 7 project be conducted (Task 5), and that a final report of findings from the analysis be prepared (Task 7). The Highway 7 project deals in part with both technical engineering and HF analyses of HUD-based in-vehicle visual enhancement technology to benefit operational driving performance under limited driving visibility conditions. The analysis reported here of an actual in-vehicle HUD complements the HF analysis of a simulated vehicle visual enhancement system (VES) carried out by Caird and colleagues [1] to satisfy the remaining tasks of the project, which is included as Appendix A to this report.

The results reported here deal exclusively with a ‘static’ HF analysis by the author of this report of the HUD installed in the Acura Integra emplaced in the University of Minnesota (UM) Division of Kinesiology Human Factors Research Laboratory (HFRL) wrap-around driving simulator. The static approach involves visual inspection of the HUD hardware and visual interface and of the simulated driving environment used for the simulation phase of the Highway 7 project, accompanied by collection of some system measurements. That is, this report does not encompass a usability analysis of the HUD, or an analysis of the effects of interacting with HUD on visual and driving performance of human operators under either simulated driving or actual driving conditions in the field.

The purpose of the Highway 7 HUD system is to benefit driving performance and safety for operators of specified service, regulatory and service vehicles who may be faced with the necessity for vehicle operation under limited roadway visibility conditions. Documenting the degree to which this goal is realized will require a systematic program of field research. The analysis reported here deals with a series of visual HF design features of the system that may influence its ultimate success.

The findings of this analysis are largely positive. The simplicity and monochromicity of the projected image avoid a large number of visual HF problems associated with use of more complex imagery and symbology in other types of aviation and in-vehicle HUDs. Use of

conformal imagery responds to other findings pointing to the superiority of conformal, as opposed to non-conformal, HUDS in supporting operator performance.

Nevertheless, some visual HF design problems with the Highway 7 HUD system are suggested by this analysis. In particular, possible design deficiencies related to lack of manual controls, binocular parallax, viewing angle, visual feedback delay, and cab safety have the potential for adversely affecting the ultimate success of the system. It may be presumed that some if not all of these design problems can and will be addressed, as project work towards operational implementation of the system proceeds.

TABLE OF CONTENTS

Page

TABLES

APPENDIX A

ABBREVIATIONS, ACRONYMS AND DEFINITIONS

accommodation	muscular adjustment of the lens of the eyes to bring an image into focus
binocular disparity	see binocular parallax
binocular misalignment	difficulty in visually fixating an image due to image distortion
binocular parallax	the difference in the position of an object seen by one eye compared with the other
CH	vertical distance from driver's seat pan to center of combiner
cm	centimeters
collimation	a display whose image appears to be focused at infinity
conformal display	features of the HUD image are superimposed spatially on corresponding features of the real world image
CVD	viewing distance from nasion to center of combiner
dGPS	differential GPS
deg	degrees
diplopia	double vision
ft	feet
GPS	global positioning system
HF	human factors
HFRL	UM Division of Kinesiology Human Factors Research Laboratory
HUD	head-up display
hz	hertz
image combiner	that component of the HUD system responsible for combining the projected HUD image with the visual image from the external environment
in	inches
km	kilometer
LCD	liquid crystal display
LCR	luminance-contrast ratio
luminance-contrast ratio	ratio of the sum of the background (L_b) plus projected HUD image (L_s) luminances to the background luminance: $LCR = (L_b + L_s)/L_b$
m	meters
Mn/DOT	Minnesota Department of Transportation
mph	miles per hour
msec	milliseconds
nasion	junction of forehead and nose
non-conformal display	features of the HUD image are coupled to environmental events, but are not superimposed spatially on corresponding features of the real world image
PC	personal computer
pct	percent

transmittance	percentage of light energy transmitted through a medium
SEH	sitting eye height (buttocks to nasion height)
UM	University of Minnesota
VA	combiner viewing angle
vergence	convergence of the eyes through horizontal rotation of each eye towards the other
VES	visual enhancement system

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Final Report

1. INTRODUCTION

This report represents the deliverable for Tasks 5 and 7 for the subject project, which specify that a human factors (HF) analysis of the visual properties of the in-vehicle head-up display (HUD) system used for the Mn/DOT-funded Highway 7 project be conducted (Task 5), and that a final report of findings from the analysis be prepared (Task 7). The analysis reported here of an actual in-vehicle HUD complements the HF analysis of a simulated vehicle visual enhancement system (VES) carried out by Caird and colleagues [1] to satisfy the remaining tasks of the project. The Caird report, which addresses Tasks 1-4 and 6 of this project, is included as Appendix A to this report. The Highway 7 project deals in part with both technical engineering and HF analyses of HUD-based in-vehicle visual enhancement technology to benefit operational driving performance under limited driving visibility conditions.

The results reported here deal exclusively with a 'static' HF analysis by the author of this report of the HUD installed in the Acura Integra emplaced in the University of Minnesota (UM) Division of Kinesiology Human Factors Research Laboratory (HFRL) wrap-around driving simulator. The static approach involves visual inspection of the HUD hardware and visual interface and of the simulated driving environment used for the simulation phase of the Highway 7 project, accompanied by collection of some system measurements. That is, this report does not encompass a usability analysis of the HUD, or an analysis of the effects of interacting with HUD on visual and driving performance of human operators under either simulated driving or actual driving conditions in the field. Findings from a study of the effects of the Highway 7 HUD on operator performance during both simulated and actual driving under degraded viewing conditions, accompanied by a detailed technical engineering description of the system, are contained in a Mn/DOT report currently under draft review (Harder, Personal Communication).

Subsequent sections of this report describe: (1) methods (Section 2); (2) results (Section 3), comprising a description of the system, followed by observations on the visual HF design features of the system, with reference to the relevant literature pertaining to visual HF design issues with in-vehicle HUDs; and (3) discussion, conclusions and recommendations (Section 4).

2. METHOD

A static analysis of the visual HF design properties of the Highway 7 HUD system was carried out with the following steps: (1) installation of system hardware in the Acura Integra emplaced in the HFRL wrap-around driving simulator; (2) visual inspection of, and collection of a series of dimensional measurements for, the installed hardware; (3) actuation of HUD plus the simulated driving environment used for the driving simulation research phase of the Highway 7 project; and (4) observations of in-vehicle visual interface with HUD and simulated driving environment both actuated.

3. RESULTS

Results presented below deal with a description of the system, a synopsis of differences in system configuration and operation between driving simulator and field installation conditions, and observations on the visual HF design features of the system.

3.1. System Description

The Highway 7 HUD system, developed by the University of Minnesota Intelligent Vehicles Laboratory, comprises the following components: (1) projector; (2) image combiner; (3) software; and (4) projected display. These components, followed by an outline of system calibration procedures, are described below.

Projector. The purpose of the projector is to project a HUD image onto the image combiner. HUD images are projected from a 10.5 in (26.7 cm) diagonal mobile LCD display (Litton Systems #46830-1, San Diego) mounted in the Acura at a position between the two front seats, to the right and behind the driver's headrest. With the back of this observer's head on the Acura's driver's seat headrest, and with the seat positioned upright and all the way rearward, the projector screen is 8 in (20.3 cm) behind the bridge of the nose.

The projector mount consists of a vertical wooden 2x4 supporting the LCD display with its suspension mount at the upper end and resting on the central drive shaft housing, and a horizontal wooden 2x4 brace stabilizing the vertical mount, placed just behind the two front seats and extending the entire width of the interior compartment. Length of the vertical 2x4 is 36 in (91 cm). The LCD display is hanging from the front of a 4.5 in (11.5 cm) horizontal projector suspension mount, whose rear end is affixed to the vertical 2x4.

Combiner. As the name implies, the purpose of the image combiner is to combine the projected HUD image with the visual image from the external environment visible through the windshield. Visual feedback from the combined image is perceived by the driver as the HUD image superimposed on the external image. Because of the position of the image combiner (below), the projected HUD image is relatively small and is superimposed on only a portion of the external image. During simulation testing, the driver looks through the image combiner (which reflects the projected HUD image to the driver) and then through the windshield to the screen in front of the car, onto which the simulated virtual environment is projected.

The image combiner consists of a horizontally and vertically planar convex (on the projector side) clear plate of glass, protected by an outer frame, and affixed by a ball mount to the ceiling of the car directly in front of the driver's head. The combiner ball mount is anchored to the car ceiling at a position customarily occupied by the mount for the drivers-side sun visor, which is replaced by the combiner. Because the image combiner can be tilted both laterally and vertically using the four degrees-of-freedom (DOF) adjustability of its ball mount, combiner orientation readily can be adjusted to accommodate viewing requirements for drivers of different heights.

The combiner measures 11.5 in (29.5 cm) wide and 6 in (15.4 cm) high, and is framed with clear 0.75 in (1.9 cm) polycarbonate. The distance from the center of the projector screen to that of the combiner is 24.5 in (36.8 cm). Horizontal distance from the center of the combiner to the windshield is 20 in (51.0 cm). For this observer, with the head positioned on the headrest and the driver's seat upright, the distance from the nasion (junction of the forehead and the nose) to the center of the combiner ranged from 6.5 in (16.5 cm) to 14 in (35.6 cm), with the driver's seat positioned frontmost or rearmost, respectively. With the seat in a comfortable intermediate distance for the author, the nasion to center of combiner distance was 11 in (28.0 cm).

Software. The software that drives the HUD projector runs on a Micron Pentium PC. The general programming approach used to generate the HUD image is as follows: (1) X and Y coordinates of the road model used for the Highway 7 project simulation testing (next paragraph) are stored in a data base; (2) during a driving simulation trial, the Micron PC is provided with a data stream of (X,Y) coordinates from the main simulation computer that correspond to the lane position of the vehicle on the simulated road; and (3) by comparing lane position coordinates with the data base of road coordinates, the software is able to generate image for the projector that provides a HUD perspective for the driver of the road ahead of the vehicle (next paragraph). In addition, at selected times during a simulated trial, the HUD computer also generates a conformal warning (next paragraph) meant to warn the driver of a hazard ahead, consisting either of an approaching vehicle in the left oncoming traffic lane, or of another vehicle parked on the right shoulder.

Projected Display. The simulated driving environment employed for the simulation phase of the Highway 7 project consists of a two-lane straight road 10 km in simulated length, with a dashed yellow center line and two solid road shoulder lines inset at a simulated distance of 12 ft (3.66 m) from each edge of the road. Both limited visibility and hazardous driving conditions, using fog and snow, can be simulated with this environment. For the simulation testing phase of the Highway 7 project, a snow covered road with limited visibility (30 m) was used. At selected times during the simulation, a road hazard also is simulated, consisting either of an approaching vehicle in the left oncoming traffic lane, or of another vehicle parked on the right shoulder.

As described above, the image combiner is used to superimpose the HUD image on a portion of the visual image from the external environment. The image projected by the HUD system described here is simple and straightforward, its primary virtue from a visual HF perspective. It is a monochromatic image consisting of a dark background on which are superimposed three solid white lines rendered in visual perspective---that is they draw closer and almost join one another, thus providing image depth perception that makes it appear that the lines are receding into the distance. When the HUD is properly calibrated (next paragraph), the driver perceives the two outside lines in the HUD image superimposed upon the two shoulder lines, and the middle line superimposed on the center line, of the simulated roadway.

At times when a road hazard is simulated during a simulated driving trial (above), a warning icon in the form of a monochromatic square (4 solid white lines in shape of square, with dark center) is added to the HUD image. When the hazard is an oncoming vehicle, the square is projected to superimpose on the left, oncoming traffic lane; when the hazard is a vehicle parked on the right shoulder, the square is projected to superimpose on the driver’s traffic lane. The square is generated to appear in advance of the hazard at a simulated distance of 350 ft between the driver’s vehicle and the hazard---this distance corresponds to the range of the radar employed during field operations with the system (Section 3.2). The system displays only one hazard icon at any given time.

HUD imaging of the road edges and center is conformal, because with proper calibration the HUD image lines denoting these features is superimposed spatially on the actual roadway features. HUD imaging of upcoming road hazards is partially conformal, in the sense that the hazard icon is superimposed on the traffic lane in which the hazard will appear, but the icon is not superimposed on the hazard itself.

System Calibration. Calibrating the Highway 7 HUD system entails the following steps: (1) the operator adjusts the driver's seat of the Acura Integra to a comfortable position; (2) the HUD, and the display of the external simulated driving environment at unlimited visibility (750 m for the application described here), are actuated; and (3) the driver adjusts the image combiner until the 3 roadway lines in the HUD image are superimposed on the actual road shoulder and center lines of the roadway in the external environment.

3.2. Field Configuration of System

An analysis of the visual HF design features of the Highway 7 HUD system under field conditions was not conducted as part of the evaluation reported here. However, informed judgment about the visual properties of the system rests, in part, upon a consideration of how the system is deployed and used in the field. Information summarized in this section was derived from HFRL personnel involved with the Highway 7 project (Chihak, Harder and Olson, Personal Communications).

It is the understanding of this author that field applications of the Highway 7 HUD system likely will be restricted to highway safety, emergency and enforcement vehicles---such as snowplows [7], ambulances, and highway patrol cars---whose service under limited highway viewing conditions may be required if not essential. Because a snowplow cab is substantially larger than that of a sedan, many of the system description features described above (Section 3.1) will not be applicable to snowplow installation and use of the system. However, given closer parallels in configuration between the cab interior of the Acura Integra used in the HFRL wrap-around driving simulator, and cabs of patrol cars and possibly some ambulances, the above system description features may be more applicable to these latter vehicles.

A major functional difference between field and driving simulator use of the Highway 7 HUD system is reliance of the former upon acquisition of Global Positioning (GPS) data to establish road position of the vehicle. Comparable to the driving simulation application, the computer driving the HUD projector in a field vehicle is provided with a data base of GPS coordinates for roadways over which the field vehicle is predicted to travel. During field operation of the system, differential GPS (dGPS) data indicating vehicle position are acquired continuously by a GPS receiver in the field vehicle at a rate of 10 hz. The HUD computer uses these data to reference vehicle position to the data base of stored roadway GPS coordinates, and to generate a HUD image of the center and shoulder edge lines of the roadway ahead (as described in Section 3.1), based on this referencing process.

A second major functional difference between field and driving simulator use of the system is that radar is used to detect traffic hazards during field operation. Data specifying hazard position, based on radar detection, is used by the HUD computer to generate a partially conformal hazard icon in the HUD image, in a manner comparable to the approach described in Section 3.1 for the driving simulation application.

3.3. Observations on Visual HF Design Features of System

Visual HF design issues associated with the use of in-vehicle HUDs are reviewed, to varying degrees of detail, by Bossi and colleagues [2], Section 2 in the report by Caird and colleagues ([1]; Appendix A), Gish and Staplin [3], Kiefer [4], Ward and Parkes [5], and Weintraub and Ensing [6]. This section evaluates the key visual HF design features of the Highway 7 HUD system, in relation to the major findings cited in these reports. Specifically, subsections below address overall design attributes, manual controls, optical properties, calibration, and operator performance issues. Relevant conclusions and recommendations supported by the observations are referenced.

3.3.1. Overall Visual HF Design Features

The overall simplicity of the display of the Highway 7 HUD system represents its most positive and attractive feature (Conclusion 1), in that limiting the display features to lines representing road center and edges, plus the occasional hazard icon, avoids the need to deal with some 13 visual HF design considerations that should be addressed when alphanumeric symbology is displayed on an in-vehicle HUD [3,5,6]. Other positive aspects of the overall visual HF design features of the system are summarized below.

Conformal Visual Enhancement. That the system display is conformal in nature represents a positive visual HF design feature (Conclusion 2). Project findings of Caird and colleagues ([1]; Appendix A) show that, relative to non-conformal displays, conformal displays have a consistent simulated driving performance advantage over non-conformal displays, for subjects evaluated during research conducted for this project. Other research also points to performance advantages of conformal, relative to non-conformal, HUDs [3,5,6].

Monochromicity. The monochrome display represents a positive visual HF design feature (Conclusion 3). Weintraub and Ensing [6] note that use of monochrome HUDs is recommended.

3.3.2. Manual Controls

Weintraub and Ensing [6] recommend that aviation HUDs be configured with a series of manual controls. Those controls relevant to in-vehicle HUDs [5] include: (1) on-off switch; (2) brightness; and (3) 'night filter' to remove unwanted display luminance during nighttime driving. It is not clear to this author if the Highway 7 HUD is intended for nighttime operations (a thermal imaging HUD [2,4] might be more appropriate for this purpose). Therefore, the need for a 'night filter' control for the Highway 7 HUD is open to question. The field version of the Highway 7 HUD has an on-off switch, but is not equipped with a brightness control (Recommendation 1). However, the position of the image combiner can be manually adjusted for calibration purposes (Conclusion 4).

3.3.3. Optical Properties

Optical properties germane to the Highway 7 HUD system include the: (1) luminance-contrast ratio of the system; (2) optical quality of the HUD; (3) combiner transmittance; and (4) collimation condition [3,5,6]. Each of these properties is addressed below.

Luminance-Contrast Ratio (LCR). The LCR refers to the ratio of the total luminance of the HUD image (comprising the sum of the projected plus background luminances) to the background luminance, where the background luminance is that of the external environment. Weintraub and Ensing [6] recommend a minimally acceptable LCR of 1.15/1, a preferred minimum LCR of 1.5/1, and a higher LCR of 4/1 for low background luminance conditions. An LCR that is too low may degrade the visibility of the projected image; an LCR that is too high may degrade the visibility of the background. However, Gish and Staplin [3, p. 9] note that, 'there is no single HUD luminance contrast that optimizes performance for all driving conditions.'

The LCR for the Highway 7 HUD system was not determined as part of this analysis, based on the consideration that only LCR measurements under field conditions are relevant to the visual HF properties of the system. The observation of Gish and Staplin suggests that adjustability of the luminance of the projected display is desirable (Recommendation 1), and that the background luminances of environments in which the system typically will be used should be ascertained (Recommendation 2).

Optical Quality. Optical quality of a HUD is of primary concern with symbolic displays [5,6], for which visual resolution of the projected symbology is required. The optical quality of the Highway 7 HUD is judged to be high---the image is not fuzzy, and the line edges are sharp (Conclusion 5).

Combiner Transmittance. This term refers to the percentage of light energy transmitted through a medium. A minimum combiner transmittance of 70% is recommended [6]. The transmittance of the Highway 7 HUD combiner was not measured as part of this analysis (Recommendation 3).

Collimation. This term refers to a display that appears to be focused at infinity—that is, light rays emanating from the display are parallel when they reach the eye. The desirability of collimation with a HUD image is a matter of controversy. With reference to aviation HUDs, some observers believe that a collimated HUD display causes misaccommodation, resulting in degraded visual performance [8]. Other observers strongly favor collimation of the HUD image [6]. Most automobile HUDs are not collimated [6]. However, Weintraub and Ensing [6] also point out that with conformal HUDs, collimation is a non-issue, inasmuch as a conformal display requires collimation. Inasmuch as the Highway 7 HUD is conformal, collimation may be judged to be a non-issue with this system.

3.3.4. Calibration

As noted above (Section 3.1), system calibration involves aligning the 3 lines projected on the HUD with roadway edge and center lines with which the HUD lines are meant to conform. This procedure raises the question of how the system is to be calibrated in the field when roadway features are obscured (for example, by fog or snow), field application conditions for which the system is intended (Recommendation 4).

A further observation made during system calibration is that the accuracy of the calibration appeared to be affected by head position. That is, the conformal accuracy of superimposition of projected lines and roadway lines in one head position was reduced if the head was shifted horizontally to another position. This observation raises the question of how head position may affect the accuracy of driving performance with the HUD in the field, under circumstances where system calibration may have been carried out with the head in one position, and field operation may occur with the head in other positions (Recommendation 5).

3.3.5. Operator Performance Issues

This section addresses visual performance issues related to operator interaction with the Highway 7 HUD. Given that human subjects testing was not carried out as part of this analysis, the evaluation below is based on observations of the author, plus informed judgment that relies upon literature reviews and findings [3,5,6]. Subsections below deal with visual accommodation and vergence, binocular misalignment, binocular parallax and diplopia, viewing angle and anthropometry, visual feedback delay, and cab safety issues.

Visual Accommodation and Vergence. These terms refer, respectively, to the visuomotor mechanisms that focus images on the retina, and those which horizontally rotate the eyes towards one another to provide depth cues. Weintraub and Ensing [6] point out that, for purposes of target detection/recognition and distance/size perception, these mechanisms operate in tandem. As noted above, the degree to which viewing of a collimated HUD causes mis-accommodation remains a matter of controversy. The author did not experience apparent difficulty in either of these performance areas during visual interaction with the system. More generally, because the Highway 7 HUD consists of 3 simple lines plus an occasional hazard icon, and lacks complex symbology, it is judged that neither mis-accommodation nor vergence difficulties are likely to notably affect visual performance with the system (Conclusion 6).

Binocular Misalignment. This term refers to difficulty in binocular visual fixation of an image due to image distortion. No apparent problems with binocular misalignment were observed by the author during visual interaction with the system (Conclusion 7).

Binocular Parallax and Diplopia. The former condition (also termed binocular disparity) refers to the position of an image shifting when viewed by one eye relative to the other due to oculomotor dominance effects, resulting in diplopia (double vision). This effect was readily apparent to the author when viewing the Highway 7 HUD during system calibration with unlimited visibility. That is, there were recurrent episodes of double vision of the actual roadway lines and the projected conformal lines. However, during viewing of the HUD under simulated limited visibility conditions (fog, with snow on roadway), this effect disappeared, because the roadway lines no longer were visible.

In the field, the system is intended for use primarily under limited viewing conditions. However, it is possible that visual interaction with the system may occur during periods of time when road visibility is not compromised (for example, alternating ground fog and clear road intervals). Under such conditions, the operator may not wish to periodically engage and disengage the system. This means that there may be periods of time when the operator is visually interacting with the HUD while driving under relatively clear viewing conditions, with the projected conformal image lines and the roadway lines both visible. Under such circumstances, effects of binocular parallax on visual performance with the system may occur [6], a possibility that merits further study (Recommendation 6).

<u>Viewing Angle and Anthropometry</u>. As outlined below, visual performance during operator interaction with a display depends, in part, upon the visual angle with which the operator views the display. For the Highway 7 HUD system, viewing angle may be calculated as:

$$\text{CVA} = \arcsin((\text{CH}-\text{SEH})/\text{CVD}) \qquad (1)$$

where

CVA = combiner viewing angle (deg)
CH = vertical distance from driver's seat pan to center of combiner
SEH = sitting eye height (distance from buttocks to the nasion)
CVD = viewing distance from nasion to center of combiner.

With the seat in vertical position, vertical distance from the pan of the driver's seat of the Acura Integra to the center of the Highway 7 HUD system combiner is 36 in (91.4 cm), a distance that is 1 in more than the SEH of the author.

For SEH, the worldwide range from the 5th percentile female to the 95th percentile male is 31.4 in (79.8 cm) to 37.8 in (96.0 cm), with a median of 34.6 in (87.9 cm) [9].

The CVD represents the most uncertain dimension, since under operational conditions this distance depends upon seat composition (seat pan compressibility) and operator adjustments to the seat (angle of seat back; elevation of seat pan), as well as SEH. Data In order to estimate the CVA across the anthropometric range of SEH levels, the following simplifying assumptions are adopted.

1. A CVA of 0 deg (e.g., nasion at same level as center of combiner) occurs at an SEH of 35 in (89 cm), which corresponds to the worldwide median for SEH [9].
2. Based on Assumption 1, a CH of 35 in (89 cm) is assumed.
3. At a CVA of 0 deg (and a corresponding SEH of 35 in), a CVD of 11 in (27.9 cm) is assumed (this is the CVD for the author at a 'comfortable' seat position).
4. In the field, the Highway 7 HUD system will be installed in 'large' cars (a reasonable assumption for patrol car and ambulance installation).
5. In large cars, females on average will sit 2 in (5 cm) closer to the HUD than males. This estimate is adapted from recent findings reported by McFadden and colleagues [10] on seating distance from the steering wheel in cars of different sizes for males and females.
6. For SEH levels different from 35 in, CVD is calculated as:

$$\text{CVD (in)} = ((35 - \text{SEH})^2 + 11^2)^{1/2} \quad \text{for males, and} \tag{2}$$

$$\text{CVD (in)} = ((35 - \text{SEH})^2 + 9^2)^{1/2} \quad \text{for females} \tag{3}$$

Table 1. Estimated combiner viewing angle as a function of driver anthropometry

Anthropometric Category	CH (cm)	SEH (cm)	CH - SEH (cm)	CVD (cm)	CVA (deg)
Median (males & females)	89	89	0	27.9	0
5th Percentile female	89	80	9	24.6 (Equat. 3)	21.5 (Equat. 1)
95th percentile male	89	96	-7	28.8 (Equat. 2)	-14.1 (Equat. 1)

Based on these assumptions, estimated CVAs for drivers across the worldwide anthropometric range of SEH levels are presented in Table 1. The estimates show that to view the Highway 7 HUD, given the system configuration installed in the Acura Integra, the 5th percentile female may have to look upwards at an angle exceeding 20 deg, whereas the 95th percentile male may have to look downwards at an angle approaching 15 deg.

A neutral (CVA=0 deg) or slightly downward HUD viewing angle can be judged to be relatively acceptable. Gish and Staplin [3] summarize research showing that both reading and visual reaction time using an automotive HUD is faster than performance with a conventional heads down information display, and that a HUD viewing angle 8 deg below the line of sight is recommended. This recommendation generally is aligned with that of Burgess-Limerick and colleagues [11], who report findings supporting the argument that the optimal location of a visual display should be at least 15 deg below the line of sight.

On the other hand, asking a driver to view a HUD located at an angle above the line of sight can be judged to likely be not acceptable. There is ample evidence from studies of computer workers that sustained viewing of visual displays at viewing angles above the line of sight is associated with an elevated risk of musculoskeletal problems of the neck and shoulder [11,12]. Ward and Parkes [5] note that in-vehicle VES HUDs will require continuous viewing, and that, 'the need to keep the eye s properly aligned with the HUD optics may force drivers into static or awkward postures for prolonged periods.' This problem almost certainly will be exacerbated if the HUD viewing angle requires the driver to maintain long periods of neck extension.

The estimates in Table 1 are based on observations of the author, plus extrapolations from the literature. They suggest that if the Highway 7 HUD system is adopted for general field use, there may be an (unknown) percentage of operators whose size may require them to engage in continuous viewing of the HUD at neck-extended viewing angles associated with a disproportionate risk of neck and shoulder problems, relative to operators with a larger body size. Further study will be required to confirm or dismiss this possibility, with studies that evaluate visual angles required for HUD viewing by a representative population of users (Recommendation 7), and that ascertain the nature and extent of possible musculoskeletal complaints, particularly those related to the neck and shoulder, associated with routine operational use of the system (Recommendation 8).

Visual Feedback Delay. One of the distinctive design features of the Highway 7 HUD system, that differs from those automotive systems described in the cited reviews [1-6], is its reliance on acquisition of GPS data indicating vehicle position for purposes of generating the conformal display. This technological approach raises two questions regarding visual performance with the system---accuracy of the positional data, and data acquisition rate.

Information provided by Highway 7 project members indicates that, because of reliance on dGPS data, vehicle positional information is highly accurate. Conversely, the data acquisition rate of 10 hz (e.g., positional updates every 100 msec) raises the possibility that delay in presentation of HUD visual feedback of vehicle position to the driver may have an effect on driving performance. The term delay refers to the fact that between successive 100 msec visual indications of vehicle roadway position on the HUD, the vehicle traverses a section of roadway for which no visual feedback of roadway position is provided.

At a vehicle speed of 30 mph (a plausible upper limit of how fast an operator might drive using the HUD under impaired visibility conditions), the vehicle traverses 4.4 ft (1.34 m) in 100 msec. This low value suggests that a positional update rate of 10 hz should have minimal effect on the ability of the operator to rely on visual feedback to guide the trajectory of the vehicle.

However, it can be argued that a visual feedback delay of 100 msec may introduce increased <u>variability</u> in driving performance that may have adverse safety implications. In a review and analysis of factors affecting variability in remote guidance of teleoperated vehicles (a task for which delayed visual feedback is an inherent feature), Smith and colleagues [13] report findings from a pursuit tracking task (driving also represents a pursuit tracking process) indicating that there is no level of visual feedback delay below which tracking performance is not degraded to some degree. In other words, there does not appear to be a decremental performance threshold associated with visual feedback delay. At a visual feedback delay interval of 100 msec, these authors report a 30 pct increase in tracking error, relative to the control (no delay) condition. This finding suggests that for field applications, given a vehicle positional update rate of 10 hz, possible effects of visual feedback delay on variability and error in visual performance with the Highway 7 HUD system merit further study (Recommendation 9).

<u>Cab Safety</u>. The Acura Integra configuration of the Highway 7 HUD system places the glass combiner between the driver and the windshield, about a foot almost directly in front of the drivers face. This configuration raises obvious cab safety concerns. A sudden impact could rapidly propel the driver's head into the combiner, with consequent potential for head, face, and/or eye injury. A risk that possible may be obviated with air bag protection. Nevertheless, possibly adverse cab safety implications of the system merit attention (Recommendation 10).

4. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The purpose of the Highway 7 HUD system is to benefit driving performance and safety for operators of specified service, regulatory and service vehicles who may be faced with the necessity for vehicle operation under limited roadway visibility conditions. Documenting the degree to which this goal is realized will require a systematic program of field research. The analysis reported here deals with a series of visual HF design features of the system that may influence its ultimate success.

As summarized under Conclusions below (Section 4.2), the findings of this analysis are largely positive. The simplicity and monochromicity of the projected image avoid a large number of visual HF problems associated with use of more complex imagery and symbology in other types of aviation and in-vehicle HUDs. Use of conformal imagery responds to other findings pointing to the superiority of conformal, as opposed to non-conformal, HUDS in supporting operator performance.

Nevertheless, as summarized under Recommendations below (Section 4.3), some visual HF design problems with the Highway 7 HUD system are suggested by this analysis. In particular, possible design deficiencies related to lack of manual controls, binocular parallax, viewing angle, visual feedback delay, and cab safety have the potential for adversely affecting the ultimate success of the system. It may be presumed that some if not all of these design problems can and will be addressed, as project work towards operational implementation of the system proceeds.

After a synopsis of the limitations of the analysis, concluding subsections below summarize conclusions and recommendations growing out of the observations made.

4.1. Limitations of Analysis

The analysis reported here is limited to the observations and informed judgment of one analyst, the author of this report. Thus, the observations, conclusions, and recommendations reported should be referenced to results from human subject testing carried out in the context of Tasks 1-4 and 6 of this project [1; Appendix A], as well as results from simulation testing and field research both concluded and anticipated as part of the Highway 7 project. None of the work to date has involved a usability analysis of the system, which should be incorporated into the system analysis plan at some point (Recommendation 11). A further limitation of the present analysis is that it is limited to an evaluation of the system as installed in the Acura Integra vehicle within the wrap-around simulator at HFRL. There are a number of important differences between laboratory and the field applications of the system in terms of system configuration, optical properties, and operator interaction.

4.2. Conclusions

Observations made during the static analysis of the visual HF design features of the Highway 7 HUD system reported here support the following conclusions.

1. The simplicity of the system display, comprising 3 lines and an occasional hazard icon, represents its most positive and attractive feature, because this design avoids the need to deal with some 13 visual HF design considerations that should be addressed when alphanumeric symbology is displayed on an in-vehicle HUD.
2. The conformal nature of the display represents a positive visual HF design feature of the system.
3. The monochrome nature of the display represents a positive visual HF design feature of the system.
4. The ability to manually adjust the position of the image combiner for calibration purposes represents a positive visual HF design feature of the system.
5. Its high optical quality represents a positive visual HF design feature of the system.
6. It is judged that neither mis-accommodation nor vergence difficulties are likely to notably affect visual performance with the system.
7. Binocular misalignment does not appear to represent a visual performance problem with the system.

4.3. Recommendations

Observations made during the static analysis of the visual HF design features of the Highway 7 HUD system reported here support the following recommendations.

1. Equip the system with a manual control for adjusting luminance level of the projected display.
2. Conduct a field LCR analysis of the system, over a range of background luminances for environments in which the system typically will be used.
3. Determine the transmittance of the system combiner.

4. Address the question of system calibration in the field when roadway features are obscured.
5. Because of the apparent effect of horizontal head position on calibration accuracy, the effect of horizontal head position on the accuracy of driving performance with the HUD under field conditions should be evaluated.
6. Possible effects of binocular parallax on visual performance with the system merit further study.
7. Evaluate the visual angles required for viewing the system display by a representative population of HUD users.
8. Evaluate the nature and extent of possible musculoskeletal complaints, particularly those related to the neck and shoulder, associated with routine operational use of the system.
9. Possible effects of visual feedback delay on variability and error in visual performance with the system under field conditions should be evaluated.
10. Possible adverse cab safety implications associated with design of the system should be addressed and evaluated.
11. Conduct a usability analysis of the system.

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APPENDIX A

Report of Caird, Horrey, Chugh, and Edwards Pertaining to Project Tasks 1–4 and 6:

The Effects of Conformal and Non-Conformal Vision Enhancement Systems on Older Driver Performance

TP 13422E

The Effects of Conformal and Non-Conformal Vision Enhancement Systems on Older Driver Performance

FINAL REPORT

Prepared for

Transportation Development Centre
Safety and Security
Transport Canada

by

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Abstract

Vision enhancement systems (VES) have the potential to increase older drivers mobility. The purpose of this research contract was to determine the viability of certain VES properties on older driver performance and preference. To achieve these objectives, a comprehensive review of VES and head-up display (HUD) literature is reported which highlights gaps and limitations in previous research. A preliminary experiment, which used digital video of suburban city streets with conformal and non-conformal VES, was conducted. Thirty-two younger drivers drove through the scenes with a video simulator where interactions with the brake and accelerator affected playback speed. Visual enhancement of a pedestrian increased perception response time (PRT) for brake responses and more people missed the pedestrian altogether with the conformal display. The primary experiment addressed older and younger driver performance during everyday driving, car following, intersection approaches, and emergency events (i.e., the sudden appearance of a pedestrian). Forty-eight participants drove either a conformal or a non-conformal VES in a fixed-base driving simulator. A greater lateral separation distance was maintained between participants and oncoming vehicles with the conformal display. PRT to the sudden appearance of the pedestrian was faster in day and fog with the conformal display than for the non-conformal display. Qualitative data indicated the utility of VES for conditions where visibility was limited. Cluttered environments such as during heavy traffic may not be conducive to enhancement. Implications of the results for the design of conformal and non-conformal VES, and future research, is discussed.

Key Words: Older drivers, intelligent transportation systems (ITS), vision enhancement systems (VES), conformal and non-conformal displays, driver attention, and perception-response time (PRT).

EXECUTIVE SUMMARY

The purpose of this research was to systematically examine the effects of two types of vision enhancement system (VES) displays on younger and older driver performance in a variety of contexts. A comprehensive review of the literature on infrared VES and head-up displays (HUDs) is presented. A VES provides the advantage of an early detection of road curvatures, pedestrians and animals, and other objects in the driving environment. Results of a literature review found that methodological limitations of previous studies often limit the generalizability of results. In particular, inadequate sampling of older drivers, the exclusive use of detection tasks only, and inadequate consideration of attention issues are identified as limitations.

A pilot experiment was conducted that used digital video of suburban and urban traffic environments to test the application of conformal and non-conformal displays. Conformal imagery directly highlights aspects of the traffic environment, whereas non-conformal displays are coupled to environmental events, but not superimposed on them. Figure E.1 (below) illustrates the non-conformal (A) display used in this study. Oncoming and parked vehicles were highlighted using these two display types. Thirty-six younger drivers (M = 23 years) interacted with the digital-video simulator through accelerator and brake inputs. While the driver traveled through a variety of roadways, a pedestrian appeared, entered the roadway, and stopped. The task of the driver was to brake for the pedestrian. Perception response time (PRT) to the pedestrian was significantly faster on each successive exposure. On one trial, either conformal or non-conformal highlighting was applied to the pedestrian. Participants responded significantly faster to the non-conformal display (Mean PRT = 0.95 s) than to the conformal display (Mean PRT = 1.21 s). Conformal highlighting of the pedestrian may have obscured the pedestrian and, thus, drivers may have required more time to detect and recognize it. The experiment guided the selection of independent and dependent variables, and the functionality of the conformal and non-conformal displays used in the primary experiment.

In the primary experiment, 24 younger and 24 older drivers used either a conformal (see Figure E.1 B below) or non-conformal VES display while driving in a fixed-base driving simulator. Within each block of trials, five traffic scenarios were used to test

driver performance; namely, everyday driving, car following, intersection approaches, emergency events, and the failure of the VES. Participants experienced three sets of trials with each set corresponding to training, driving in daylight and in fog conditions. In an everyday driving trial, a participant traveled through city streets that varied in the number of oncoming and parked vehicles. Lateral separation distance between the participant's vehicle and other parked and oncoming vehicles was measured. Display type (i.e., conformal or non-conformal) did not affect separation distance to parked vehicles, but did increase separation distance to oncoming vehicles for those that used the conformal display. Increased separation distance to oncoming vehicles appears to be a benefit of conformal displays.

In the intersection scenario, the traffic light would change on 50% of the trials as drivers approached the controlled intersections. On trials where the light changed, stopping before entering the intersection was a challenge by rendering the all-red phase of the light change quite short (1.3 s). As a result, almost two-thirds of participants ran the stoplight on the two baseline trials. The response type of stop or run the light revealed several interesting results. First, more older drivers ran the stoplight than younger drivers which may be indicative of generalized slowing or cautiousness in responding. Second, those with a conformal display ran fewer lights than those with the non-conformal display. Drivers using the non-conformal display must scan the environment for the coupling between their display and the presence of an important environmental feature. This additional scan time may have reduced the time available to stop. With the conformal display, the intersection light was highlighted on several trials and was perceived favourably by participants. However, quantitative analyses were precluded due to low cell counts.

The pedestrian scenario was an emergency event. When a pedestrian suddenly appeared in the roadway, the task of the driver was to respond to avoid hitting him. This was a difficult task to achieve within 2.3 s (i.e., the average time-to-collision). The pedestrian appeared only twice throughout all the trials; once in the day, and once in the fog. When first encountered, 18 of 43 participants struck the pedestrian. In the fog trial, 13 drivers did the same. The response type made by these drivers was to brake, but too late to avert collision. Steering and braking was a more effective response. Those that used the conformal display had faster PRTs to the appearance of the pedestrian than those that used the non-conformal display. Attentional focus on the non-conformal display may have delayed a response to the emergency event.

When a simulated conformal VES failure indicated that a vehicle was approaching in the driver's lane when it was not, most participants stopped because the errant blue bar in their lane was perceived as a threat.

Subjective impressions of the conformal and non-conformal systems, once experienced, were exceptionally interesting. The perceived benefits of VES systems are in situations where visibility is limited by either weather (e.g., fog, snow, rain), time of day (e.g., nighttime, dusk) or roadway geometry (e.g., curves, railway crossings). Results demonstrate that VES devices may distract—especially when unexpected events occur. Less than one-quarter of participants said they would use a VES with regularity if it were installed in their vehicle. Although separation distance increased when oncoming vehicles were highlighted with a conformal bar, enhancement of parked and oncoming vehicles was thought to be of questionable use. Independent of driving scenario, conformal displays appear to have a performance advantage over non-conformal displays. These advantages, however, are dependent upon what is highlighted and if a highlight covers or obscures important environment information.

The present research fills a gap in knowledge about older driver performance with conformal and non-conformal VES in the fog. Like most research, many more questions were raised than answered. Although parked cars and oncoming vehicles were highlighted in the experiments, the attentional and response difficulties identified here are likely to generalize to situations where highlighting has been applied in other ways. The consistency in application of highlighting to meaningful environmental objects and traffic events, the reliability of VES to display accurate information, and the effective integration of new visual cues into control and tactical driving are desirable, but poorly understood, design properties of VES. Research on long-term use and performance patterns with several promising VES prototypes is needed. Performance tradeoffs between scanning the environment, which is required with non-conformal displays, and traffic information that may be obscured (which is possible with conformal VES) require prolonged exposure to determine the relative safety implications of each system type.

1.0 INTRODUCTION

With increased age, drivers lose their visual capability through disease and natural degeneration (Kline & Scialfa, 1997; Owens & Andre, 1996; Schieber, 1994). Frequently, older drivers choose not to drive when winter and nighttime driving conditions exist (Caird, in press; Caird, et al., 1998). Vision enhancement systems (VES) provide visual information about the roadway ahead such that curves and hazards can be anticipated. Vision enhancement systems have shown promise to increase and restore the mobility of older drivers (Mitchell, 1997; Mitchell & Suen, 1997; Oxley, 1996; Suen & Mitchell, 1997). VES have the potential to increase mobility and safety when weather and driving conditions are not optimal. These conditions are common in Canada. In addition, many multi-national automobile manufacturers have focused on the production of VES products in their research and development programs. These social and technical currents taken together form the background with which the present studies were conducted.

1.1 Project Overview

The studies reported here examined to what extent younger and older drivers were able to successfully interact with vision enhancement systems in a variety of traffic situations. Two types of vision enhancement systems were presented in a head-up display (HUD) format as participants engaged in a series of pre-defined routes in a driving simulator with different environmental conditions. It was expected that VES displays would prepare drivers to upcoming events to the degree that information was tightly coupled to required driver behavior (e.g., stopping at an intersection or steering around an obstacle). When VES information is displayed, what is less clear, is how irrelevant information will affect older driver performance. For example, older drivers may find the display of VES information distracting or useful, depending on the situation. Also, how the presence of VES information affects driver responses to critical non-highlighted events (i.e., events that are not enhanced by VES). What is not understood from previous studies on VES, reviewed in Section 2, is how improved detection distances afforded by VES is integrated into vehicle control and emergency response behaviours. For example, HUDs have a number of attentional, optical, and content issues which impact driver performance (see, e.g., Caird & Chugh, 1997; Gish & Staplin, 1995; Tufano, 1997).

The experiment was conducted in the Human Factors Research Laboratory (HFRL) at the University of Minnesota using a flat-screen driving simulator. In general, the application of driving simulation is necessary where traffic scenarios are too dangerous to test drivers in an actual setting, where the impact of a new technology on driver performance is unknown, and where field tests cannot adequately control for extraneous variables. Here, the safety of older participants was preserved as they encountered unexpected events while driving with a vision enhancement system. A means for simulating conformal and non-conformal types of VES display was developed and integrated into existing driving simulation software. Specifically, conformal and non-conformal VES displays were designed and tested. The experiments required participants to attend to the most important information in a dynamic driving environment as they interacted with some of the information provided by the VES displays. Simulated traffic routes and emergency events were encountered by participants. Thus, the primary issue addressed by the reported experiments is the degree that predictable and unpredictable traffic events affect driving behaviors of younger and older drivers using VES displays.

Groups of older and younger drivers were given a standard test battery of visual acuity, and contrast sensitivity at the start of a simulator session. Various random presentations of the displays and counterbalancing schemes were used to avert order effects and asymmetric transfer difficulties. During training, a variety of baseline measures were taken such as vehicle separation, response type to different traffic situations, perception-response time (PRT), braking distance to a lead vehicle that braked, response time accuracy and errors with either display. The primary tasks were to control the vehicle on the roadway and to avoid obstacles and other vehicles just as they might when operating their own vehicles.

1.2 Project Objectives

The specific objectives of this research were to:

- Review the literature in cognitive science, human-computer interaction, transportation ergonomics, and attention as it relates to vision enhancement systems (VES) and head-up displays (HUDs);
- Develop an experimental design of VES displayed in a HUD that examines the most pressing attentional issues for older drivers;
- Determine the effect that form (i.e., conformal, non-conformal) and predictability of VES has on driver performance given various weather (e.g., fog) and road conditions (e.g., intersections and car following);
- Empirically examine the degree to which older and younger drivers' visual attention is affected by the VES (i.e., vehicle control and emergency event response);
- Determine the consequences of vision enhancement information that is in conflict with the state of the world (e.g., the VES system indicates a vehicle is approaching in the driver's lane when it is not); and
- Build collaborative relationships between governments, institutions and corporations. The University of Minnesota's Human Factors Research Laboratory and Center for Transportation Studies, Transport Development Centre of Transport Canada, and the University of Calgary's Van Horne Institute for International Transportation Studies participated in the execution of this research.

Subsequent sections of this report address these objectives.

2.0 LITERATURE REVIEW

A review of head-up display (HUD) and vision enhancement system (VES) literature is provided so that system design trends, human factors empirical results, and methodological issues can be examined. The purpose of vision enhancement systems (VES) is to increase a driver's ability to see critical hazards (e.g., pedestrians and bicyclists), hazardous objects (e.g., guardrails and black ice), and the roadway (e.g., edge lines), especially during low visibility conditions (i.e., thick fog, rain, snow, and nighttime) (Kyle, 1997; Parkes, Ward, & Bossi, 1995). VES are implemented in head-up displays (HUD) which present information on the forward field of view of drivers (i.e., on the windshield), or in a dashmounted display (Flannagan & Harrison, 1994; Gish & Staplin, 1995). To date, HUDs have received widespread application in aviation, but have had limited application for driving. HUDs allow drivers and pilots to monitor instrument information while keeping their eyes directed towards the external environment. Because their eyes remain up, fewer downward glances are needed to obtain information. Different types of information may appear in an automotive HUD including speed, hazard signals, and vehicle warnings such as engine problems (Gish, et al., 1999).

Conformal imaging is represented by imagery in a HUD that is overlaid on the traffic environment, so that the image is collimated at the same location as the object it augments (Gish & Staplin, 1995; Wickens & Long, 1995). The conformal image offers an additional source of information (about the object) for the driver. Conformal imagery is unique to HUDs because it displays information in the near domain (i.e., the windscreen) optically superimposed on objects in the far domain (i.e., external environment) such that they form a single object. As conformal images are overlaid on the external environment, it is essential that placement is at reliably close focal distances to the objects as seen by drivers (Tufano, 1997). Conformal imaging is different from non-conformal HUDs. Non-conformal HUDs are collimated at a depth of 2.5 to 4 m in front of the driver (Gish & Staplin, 1995), and to date have typically presented speed, turn, or hazard signal information, but may also contain information about the traffic environment such as cars and pedestrians. Conformal images are more likely to incorporate shapes and abstract forms rather than the alphanumeric information that is often presented in non-conformal HUDs.

2.1 HUD Research with Vehicles

A comprehensive review of vehicle HUD literature was performed by Gish and Staplin (1995). As with other reviews, attention issues were based largely on aviation reviews (e.g., Weintraub & Ensing, 1992). Extrapolating to automotive HUDs, Gish & Staplin (1995) presented an extensive list of variables that may impact driver behavior. These included features of the HUD, presence of distracters in the environment, the number of response alternatives available to drivers, and the effect of emergency events, among others.

Physical features of the HUD (e.g., legibility, brightness, character size, colour, contrast) (Okabayashi, et al., 1989; Okabayashi, et al., 1991; Inuzuka, et al., 1991) and spatial location (i.e., HUD vs. head-down display or HDD) (Fukano, et al., 1994; Kiefer, 1991; Sojourner & Antin, 1990) are the most commonly cited variables. Other variables studied are display luminance (Bossi, Ward, & Parkes, 1994), driver alertness (Iino, Otsuka, & Suzuki, 1988), usability of HUD navigation interfaces (Steinfeld & Green, 1998), and external target location (Bossi, Ward, & Parkes, 1994; Sojourner & Antin, 1990). The most common finding is that it takes less time to retrieve information in a HUD than a HDD (i.e., head-down display or instrument panel) (Caird & Chugh, 1997; Hooey & Caird, 1996; Kiefer, 1991; Soujouner & Antin, 1990).

Ward and Parkes (1994) reviewed safety factors associated with the physical properties of vehicle HUDs. Because HUDs are presented at focal distances different from external objects there is the possibility of mis-accommodation whereby objects appear further away than they actually are. Similarly, if HUD images are presented at optical infinity, the objects in the real world may appear to pass through display imagery. This may be disruptive for drivers, especially if the HUD image is conformal (also, see, Tufano, 1997). Natural head movements by drivers may distort HUD images or render them not visible (Ward & Parkes, 1994). Distortions could result in visual masking of external objects. Light from external sources (e.g., other vehicle headlights, moonlight) could produce reflections which would adversely affect the driver's ability to detect other objects in the forward and periphery fields. HUDs are prone to luminance contrast differences between the HUD image and the external environment, which may render the HUD too bright or not bright enough. The brightness of the HUD image itself may inhibit dark adaptation at night resulting in a reduction in ability to detect low luminance objects in the environment. Older drivers may be adversely affected due to natural declines in contrast sensitivity and susceptibility to glare. Finally, HUD information needs to be accurate. If it is unreliable or conflicts with external information, it may confuse drivers or reduce their confidence in the device (Ward & Parkes, 1994; Chugh & Caird, 1999).

Tufano (1997) suggested that studies in automotive HUDs have a bias to overlook attention issues as evidenced by the methodologies adopted. With HUDs, information is extracted from both the near and far domains concurrently. With a traditional HDD instrumentation panel the switch of attention is readily apparent because of three strong cues associated with the switch: lens focal adjustment, ocular vergence adjustment, and gaze shifting through eye or head movements (Tufano, 1997). With HUDs, these cues are missing and therefore shifts of attention between the near and far domain may be degraded, resulting in cognitive capture. Cognitive capture occurs when there is inefficient switching of attention between the HUD and the external environment. Inefficient switching is of paramount importance as it may result in missed external objects and/or delayed responses. There have been documented cases of cognitive capture in the aviation literature, with non-conformal HUDs (Fischer, Haines, & Price, 1980; Weintraub, Haines, & Randle, 1985; Wickens & Long, 1995). Aviation research has shown that detection of unexpected events is problematic when using HUDs due to cognitive capture (Fadden, Ververs, & Wickens, 1998).

Gish and Staplin (1995) have suggested that cognitive capture may be a factor in conditions of high workload and high temporal uncertainty (low expectancy). Thus in driving, an important question is whether speeded information acquisition with HUDs is justified if cognitive capture is a common occurrence during heavy traffic conditions? Another attention issue is outlined by Gish and Staplin (1995) who stated that non-conformal automobile HUDs should be avoided as they may distract attention from the external environment (the primary source of information) (e.g., pedestrians, other cars). These attention issues point to conformal imagery as a possible solution. Conformal imagery would mitigate the need to switch attention between the near and far domains because the imagery and external environment would form a single perceptual object. Conformal imagery must however be in dynamic registration with the external object that it represents and be presented at the same optical distance as the object (Tufano, 1997).

The distinction between the "what" and "where" visual systems is important to understanding the impact of HUDs and VES on driver performance. The spatial vision (or "where") system guides visual attention to relevant locations in the environment (especially the periphery) (Egeth & Yantis, 1997; Posner & Dehaene, 1994). The spatial vision system is involved in detecting motion and dynamic forms, whereas the "what" or object visual system is involved in the analysis of physical properties of visual objects. In normal driving conditions, a driver's attention is distributed according to a visual search strategy, a top-down or goal directed process. However, visual search is also mediated by bottom-up (stimulus driven) events that draw attention to certain features in the environment such as motion, colour change, orientation change, and luminance increases and decreases. Thus, visual search strategies may be made ineffective by HUDs if they distract or interfere with a driver's normal search patterns. This is of concern especially when the head-up imagery is non-conformal. The spatial vision system may become activated by the appearance of non-conformal HUDs and thus distract attention from other, less salient but more critical events. The potential exists for non-conformal HUD imagery to clutter and mask critical information.

In the same paradigm, conformal imagery would be less problematic as objects displayed actually exist in the far domain. Thus the salient features of the HUD can be complementary to the activities of the spatial vision system. Several studies in aviation have demonstrated the benefits of conformal displays. There has, however, been criticism of these displays as well. Ward and Parkes (1994) suggest that conformal imagery may be problematic in periods of low visibility. Under these conditions, a visually enhanced area may demand more attention than it would under normal conditions.

Fadden, Ververs, and Wickens (1998) recently conducted a meta-analysis of HUD studies. Their review included a study of the independent variables of display location, conformal imagery, task type, and expectancy were reported. Only 4 of the 18 studies included in the meta-analysis were driving studies; the others were from the aviation domain. The primary dependent measure in these four driving studies was detection of various objects. One study measured tracking performance. They found that the benefits of HUDs are often affected by the format in which they are presented (i.e., conformal or non-conformal), along with user expectancy about the frequency of certain traffic events. The meta-analysis showed that detection is enhanced when HUD users expect the appearance of targets. The meta-analysis also demonstrated benefits of conformal imagery for tracking and detection. However, this particular analysis was entirely based on aviation studies. It did not include any driving studies as none of the four driving studies used conformal imagery as a variable. Thus, there is a need for experimental research in the driving domain with conformal HUDs.

2.2 Infrared Vision Enhancement Systems

VES have taken several technical paths, one of which is infrared. Infrared VES use on-board infrared sensors to detect thermal energy differences in front of the vehicle. These thermal energy differences are then turned into a heat picture displayed on the windshield with a head-up display (Kiefer, 1995; Lunenfeld & Stephens, 1991). For example, a pedestrian has a thermal signature that is different from the traffic environment background. Thus, the sensor-display VES renders the difference as a heat image of the pedestrian, regardless of the colour of the pedestrian's jacket or the amount of light.

Thermal energy is a form of emitted radiation that is not visible to the human eye (i.e., outside the range of 380 to 700 nm). Infrared sensors can detect radiation of longer wavelengths of 0.8 to 2 m (near infrared), 3 to 5 m (middle infrared) and 8 to 12 m (far infrared) (Kiefer, 1995). Once an infrared sensor detects differences in thermal energy between an anterior object and its background, then the sensed heat differences are transformed into a heat picture that is produced in the visible spectrum. The transformed thermal image is displayed on the windshield, in real time, using HUD technology (i.e., collimators and combiners). A collimator bends the light rays from the source using refraction (lenses), reflection (mirrors), and diffraction (holograms) so that it is visible on the windshield at a set focal distance from the driver's eyes. A combiner, located between the driver and the windshield, is then used to amalgamate the head-up display image with the external environment (Gish & Staplin, 1995).

Current HUD technology, based on infrared sensors, uses monochromatic images and may provide drivers with a field of view (FOV) of approximately 15 horizontal by 10 vertical (Bossi, et al., 1997). The sensor is attached to the vehicle at a position that is unavoidably different from the driver's visual reference point. This FOV is placed at the center of the driver's line of sight. Vision enhancement in peripheral vision is especially needed for older drivers who are susceptible to a restriction of the useful-field of view (UFOV) with increasing age. As such, older drivers would benefit from an expansion of the FOV. With a monochromatic display, the vision enhancement image is a distribution of black and white. A polarity setting of "white-hot" shows hotter temperature objects as whiter than colder objects, whereas, a setting of "black-hot" shows hotter items as blacker than colder objects (Kiefer, 1995). The driver would need to gain practice and familiarity with a polarity setting before using the system. During low illuminations only the "white-hot" polarity setting would be effective.

2.3 VES Research with Vehicles

A number of research agencies, both in Europe and the United States, have performed experimental research with VES and HUDs. The focus of these tests has been to examine driver performance and subjective judgments of simulated and prototype systems. These experiments were also reviewed in Caird et al. (1998).

Nilsson and Ålm (1996) performed a simulator study with three conditions: driving in fog with or without a VES, and normal driving (without fog) in a Saab Automobile AB. The VES simulation was created by taking a black and white image (17 x 12 cm) from a normal (without fog) drive, and presenting it on a monitor positioned at the center of a windshield area directly in front of the driver's forward line of sight. Thus, the center view of the participant was clear black and white, while the periphery view was foggy.

Testing with 24 participants, Nilsson and Ålm (1996) found that the use of the simulated VES during fog significantly increased driver speed in the fog condition, but did not increase the speed driven in the normal visibility level. Variability in speed and vehicle lateral position was highest when the VES was used. Brake reaction time and distance traveled after the presentation of the simulated, unexpected event, were equal in the normal and fog + VES conditions. While the results suggest that the simulated VES enhanced drivers' ability to drive faster and respond quicker to unexpected events during fog conditions, the VES itself did not effectively replicate a real VES. Understandably, if all critical objects appeared in a black and white image, then reaction times and speed selection would be comparable to a colour clear visibility version.

Nilsson and Ålm (1996) noted, from scrutinizing unexpected event responses, that participants used different strategies in interacting with the VES. Those who responded faster (M = 0.76 s) were deemed to have been using the system extensively, while others who responded slower (M = 1.25 s) were thought to be uncertain about how to divide attention between the vision enhancement display and the external environment. The inability of drivers to divide attention appropriately was identified as a potential risk factor that could complicate the driving task. To conclusively determine whether or not different strategies of VES interaction are acquired, requires the manipulation of strategy acquisition.

Nilsson and Ålm (1996) also assessed the mental workload of the 24 participants using the NASA-TLX (Hart & Staveland, 1988). The participants reported lower mental and physical demands while driving in fog with the VES than without the system. Mental effort and frustration sub-scales were higher for driving with the vision enhancement display. Vision enhancement seems to reduce mental and physical demands, while increasing perceived effort and frustration.

Ward, Stapleton and Parkes (1996) tested gap acceptance and time-to-coincidence (TTC) judgments in a lab environment using videotaped thermal images taken from a far (8 to 13 microns) infrared sensor. Gap acceptance was taken to mean, "is this gap wide enough for my vehicle?", rather than, "is this gap in traffic large enough for me to pull out safely?", which is the more common meaning. The thermal images were in both black-hot and white-hot formats. Sixteen participants, 8 male and 8 female, evenly selected from two age groups (below 25 and above 55), participated in the study. Two types of night driving scenarios were videotaped with visible light and infrared cameras. The participants were seated inside a car and the videos were displayed on a projection screen that presented a 25.5° vertical by 38.2° horizontal view.

The gap acceptance scenarios were videotapes of an automobile's approach to two foam obstacles placed at five different separations, ranging from 200mm greater than the width of the car to 200mm which was less than the width of the car. The middle three distances were +100mm, 0mm, and -100mm. If the distances between obstacles were correctly perceived, the car would pass between the obstacles at +100mm and +200mm distances and would strike the foam obstacles at the distances of 0, -100, and –200 mm. The videos were recorded at two approach speeds: 20 mph and 40 mph. Each participant was asked to press the brake if the gap was judged to be too small for the car to fit through the obstacles. Participants pressed the accelerator if the gap was judged to be adequate.

Driver responses with infrared images showed a greater number of correct rejections than with visible light nighttime viewing. In other words, drivers were able to respond more accurately for gaps that were of inadequate size with the VES than without. Correct acceptances were, however, higher with visible light viewing. This suggests that drivers responded more accurately to gaps of adequate size with normal viewing than with the VES. Equally plausible, perceptual learning of visual enhancement cues may provide advantages with sufficient exposure. Ward et al. (1996) hypothesized that drivers become more conservative with their decision criteria when using the VES. Analyzing only the correct responses, Ward et al. (1996) found that driver reaction time was significantly faster with the VES than without, especially for the extreme sized gaps (+200 mm and -200 mm).

The second scenario was videotaped by driving the test vehicle by a stationary vehicle (i.e., passing on one side). These approaches were videotaped at 20, 30 and 40 mph. Participants were shown these approaches twice in random order, and at 1, 2, and 3 seconds (corresponding to the three speeds) before a black screen occluded participants' views of the remaining 1, 2 or 3 seconds of video. The task was to press the brake when initial contact was perceived.

For TTC judgments, the type of infrared image (black-hot or white-hot) made a significant difference. Mean TTC error was higher with white-hot images than both black-hot and normal viewing. As the occlusion period increased, so did response error, ranging from 0.5 s at 1 s of occlusion to 1.39 s at 3 s of occlusion, which is consistent with the underestimation of TTC (see, e.g., Caird & Hancock, 1994). Judgments also significantly differed with speed, as higher speeds yielded more accurate results.

Bossi et al. (1997) tested the effect of a VES located in the foveal area of the driver's vision on detection of objects in the periphery. They took a daytime drive video segment and superimposed Landolt C's at various eccentricities (10° to 25° in 5° increments) on both sides of the foveal center of a driver's fixation. (A Landolt C can point left, right, up, and down and the observer indicates the direction it points.) These C's formed peripheral targets that were to be detected by 13 (6 male and 7 female) participants. The segment was degraded to simulate dusk and nighttime driving. To simulate a VES, a daytime 15° x 10° center image was superimposed on degraded segments.

Participants were asked to point a laser, mounted on a steering wheel, at the rear license plate of a leading car that was present throughout the test. This task was intended to simulate the primary tracking task in driving. The secondary task was to press the brake when a Landolt C was seen (i.e., detection) and to respond verbally to the direction that the Landolt C pointed (i.e., identification). Each target was presented for 200 milliseconds. Four conditions were tested: night driving, dusk driving, night with simulated VES, and dusk with simulated VES.

Results showed that night + VES had the fewest number of targets detected and identified at all target eccentricity levels (i.e., 10°, 15°, 20°, and 25° on both sides of the VES image). The number of targets detected and identified was consistently and significantly higher without the VES than with the VES in nighttime driving. No such difference was found for dusk conditions. More central targets (i.e., 10° and 15°) had greater decrements of detection and identification with night VES when compared to decrements of periphery targets greater than 20°. Night responses were, in general, poorer than dusk conditions, regardless of whether the VES was used.

These results reveal the adverse effect of an infrared VES on detection/identification of periphery targets in nighttime driving. As more central targets were detected to a lesser degree than more peripheral targets, this suggests that the simulated system's increased brightness (as it was taken out of daytime driving) tended to reduce the contrast of near peripheral targets.

Ståhl, et al. (1994) tested a VES for Jaguar using near infrared technology. The thermal image provided a field of view of 17.6° vertical and 12.8° horizontal. The image was projected on a flat pane of glass placed below the windshield. Fifteen elderly drivers (11 male and 4 female), who ranged in age from 65 to 80 years, drove on a 1.1 km airfield track twice, once with a VES and once without. The order of use was counterbalanced in the two drives. Drivers were asked to make a verbal response when they saw particular objects on the side of the track. The objects were dummies of an adult and a child, a large road sign, a small road sign and a set of traffic cones.

Verbal responses showed that the dummies were seen earlier with the VES than without by 13 of the 15 participants. Average detection benefits were 48 m for the adult dummy, and 63 m for the child dummy. The earlier detection of the dummies ranged from 12.5 m to 112.5 m sooner with the VES. Eight of the 15 drivers saw the cones sooner with VES, with average earlier responses of 19 m, ranging from 12.5 to 87.5 meters.

A test was also performed at night on the visibility of a live pedestrian who was standing 100 m ahead a VES equipped car. Participants were seated in a stationary car looking forward through the windshield. The test was performed first with low beam headlights, then with high beam headlights and finally with low beam + VES system. It is not clear if the order of the testing procedure was counterbalanced between participants. Thirteen of 15 participants could see the pedestrian in the low beam + VES condition, 11 with the high beam headlights and none with low beam headlights.

Most of the participants reported that the system was easy to use and interpret, with a few exceptions. The restricted size of the image enhancement was thought to be a problem by some participants. Slightly more than half of the participants responded that they would drive more at night with the system. Only four of the 15, thought the VES would result in increased confidence while driving, and one recognized the perils of overconfidence with the system. All respondents felt safe using the system, but when asked if they would drive with the VES at night "the oldest subject ... thought the enhanced light was too bright and the field of vision too narrow" (p. 2006). Recommended improvements by the participants were widening the FOV and increasing the resolution of the enhanced image.

Ward, et al. (1994) tested a prototype infrared VES during nighttime driving conditions with five participants in a field experiment. The VES image was displayed on the driver's windshield using a conformal monochromatic green HUD, with a field of view of 13°. It was not indicated whether the FOV of 13° was in the horizontal or vertical direction. Ward et al. (1994) mentioned that infrared sensors process thermal energies of a wavelength range of 8 to 13 m, which is in the far infrared range.

The five participants were provided with one hour of practice with the VES before testing, within a two-week period prior to the experimental field test. In these practice sessions the functioning of the VES was explained and the participants were provided with the opportunity to drive with the VES at night. A driving route of one kilometer in a rural area was selected for the field test. Along this road, three pedestrian silhouettes (head and torso) were constructed from plywood material. A large coat was placed on each of the silhouettes. Each participant drove the route 20 times; 10 times in each direction. All tests were performed during nighttime conditions.

A driver's task was to identify the side of the road at which the three pedestrian silhouettes were standing, by manipulating a washer/wiper switch located near the steering wheel. Silhouettes were randomly presented along the route. Two of the silhouettes were placed on one side of the roadway (right or left), and the third was placed on the other. Not all of the silhouettes were upright during a particular drive. From the description provided by Ward et al. (1994), it was not possible to determine whether the three locations of the silhouettes were randomized, changed between the 20 drives or between the five participants. At the start of the 17th drive, the VES was shut down to simulate failure.

Mean speed was calculated using the time required in driving through the route. As the number of trials rose from the first to the 20th, so did the speed for driving both with and without the VES. Thus, as the participants became more familiar with the route and VES, they drove faster. In contrast to Nilsson and Ålm (1996) findings of increased speed with a simulated VES (during simulated fog conditions), Ward et al. (1994) found a reduction in vehicle speed when using the field VES as compared to without (during nighttime driving). Speed variability was significantly higher when using the VES, which is similar to Nilsson and Ålm's (1996) results. Reaction time to the appearance of pedestrian silhouettes was not significantly different between VES and non-VES tests, but this result may be indicative of limited power or learning across events. Driver speed for the simulated failure of the VES did not differ from speed during non-failure VES drives. There was no significant difference in pedestrian silhouette detection times between drives with and without the VES. No further analysis or interpretation was provided. The implications of the system failure were difficult to interpret.

Ward et al. (1994) also assessed mental workload (NASA-TLX) five times in the study: after the first, fifth, tenth, seventeenth (i.e., the simulated failure) and the twentieth runs. Overall NASA-TLX scores showed significantly higher levels of mental workload when using the VES than when driving without the VES. Overall mental workload scores did not significantly change across trials. Of the six NASA-TLX sub-scales, mental effort and mental demand indicated a difference between VES and non-VES conditions, with higher scores reported for the VES condition. The overall mental workload scores were not significantly affected by the simulated system failure.

While the Ward et al. study (1994) was "preliminary", it suffers from numerous design weaknesses. In particular, a sample size of five participants is too small to generalize results. This is especially so when making comparisons between conditions on mean speed, speed variation and overall mental workload. One hour of training does not necessarily ensure that drivers are familiar with a VES. Base levels of perception response time were not reported. The three pedestrian silhouettes were placed in the same location throughout the 20 drive-bys, which would allow drivers to anticipate the appearance of the silhouettes.

Gish, Staplin, and Perel (1999) conducted a field study of a mockup VES. A group of four younger (26-36) and four older (56-70) participants drove in an instrumented van that collected a variety of dependent variables. The two routes that participants drove at night were on and around an airstrip in Pennsylvania. The primary independent variables manipulated were: VES display (unaided versus aided), glare (present or not present), target (deer, pedestrian, gray square, and grating), and target positions (right or left edge) (pg. 5). Detection distance was the primary dependent variable.

The sensor used for the VES mockup was a CCD monochrome camera (Hitachi KP-160) (p. 7) with enhanced near-infrared sensitivity (NIR) sensors. Display camera output was on a monochrome monitor (12 ° horizontal by 9 ° vertical) which was about 20 inches from the driver and 10 ° below the line of sight (pg. 7). Drivers were instructed to follow the verbal route guidance given by the experimenter and to maintain their speed within 5 mph of the posted speed limits. If a target appeared, they were to respond verbally when they first detected it by saying "target" and to identify the target (e.g., "deer").

The display by glare by age interaction was significant. Detection performance differed between younger and older participants. Younger drivers detected targets at longer distances with and without the VES display than older participants. Glare effectively halved the target detection distance. Older drivers reported that they were often uncomfortable looking down at the VES display, whereas the younger participants were much more receptive to using the technology. This study was limited by sample size, the statistical analysis, and potential design confounds. Improvements to VES test protocols included detection and recognition performance suggestions, and considerations of system and user-limited performance.

2.4 Summary of VES Research

Responses to some targets within the VES have improved as drivers have been given more exposure in both laboratory (e.g., PRT decreases for unexpected events) (Nilsson & Ålm, 1996) and field (e.g., earlier detection) (Ståhl et al., 1994) experiments. These are expected benefits of VES suggesting that earlier perception of hazards will result in earlier responses to the hazards, possibly avoiding late detection errors. While responses to events in the VES may have improved, perceived mental effort and demand (Ward et al., 1994), and frustration (Nilsson & Ålm, 1996) have increased when using a VES. Prolonged use of VES placed at less than optimal distances from driver eyes results in eye fatigue and dizziness (Milton, 1997). Outside the narrow visual range of a VES, responses to targets in the periphery have degraded (Bossi et al., 1997). Speed and lane deviation measurements with VES have, however, revealed non-convergent results. Although driving speed has risen with increased exposure to a VES in the laboratory (Nilsson and Ålm, 1996), it has decreased with exposure in field tests (Ward et al., 1994). Given the methodological concerns with previous VES studies and the questioned fidelity of infrared test systems, coming to consensus on the effects of specific dependent measures is difficult.

2.5 Methodological Issues with HUD and VES Research

Given Gish and Staplin's (1995) expansive list of possible independent variables, many remain untested with automotive HUDs. To date, most of our knowledge on these issues derives from the aviation literature. The generalizability of these findings to the driving context must be made with caution, especially as user tasks, environment, user population, and timing of events differ considerably between flying and driving. For example, during takeoff and landing, pilots experience high workload and greater task demands than generally experienced by drivers. Meanwhile, the spatial constraints of the driving environment consistently result in greater response urgency for critical events. Objects and obstacles in the external environment are also more salient guidance cues in the driving context. Drivers have to constantly monitor the external environment for encroachment of obstacles, while pilots may rely on in-plane instruments for guidance under conditions of low visibility. Finally, the driving population is more heterogeneous, suggesting that the usability of HUDs and VES must reflect a wider range of user capabilities.

In the HUD studies reviewed by Gish and Staplin (1995) a number of dependent measures have been used. Ideally, dependent measures should reflect performance on the primary driving tasks of steering, accelerating, and braking. Measures should thus focus on a driver's ability to keep their vehicle on the road, detect critical objects (i.e., pedestrians) and respond accordingly (i.e., brake). Such measures have high ecological validity because they relate directly to the driving environment. Some studies have, however, used dependent measures that do not directly relate to primary driving tasks. For example, Bossi, et al. (1994) asked participants to brake to

Landolt Cs that appeared in a HUD. While the braking response represents an ecological measure, drivers do not encounter Landolt Cs in the normal driving context. This was however one of the few studies that incorporated a tracking-like task in their design. Other less valid studies have asked participants to discriminate between a 20 mrad circle and square (Fukano et al., 1994) or detect speed variability in a head-up speedometer (e.g., Sojourner & Antin, 1990).

The VES studies reviewed have a number of common experimental design, measurement, and methodological strengths and weaknesses. Most of the studies reviewed had nominal peer review and were published in a conference proceedings or technical report format. Obtaining a sample of participants appears to be a matter of convenience for many studies rather than based on sampling criteria which may increase the generalizability of a study to the driving public. Ward et al. (1996) and Ståhl et al. (1994) included an older driver sample, but unfortunately, a precise description of the characteristics of these participants was not reported.

Complete descriptions of methods, sample characteristics, statistical analyses, and interpretive caution were generally lacking. Nilsson and Ålm's study (1996) had a number of desirable experimental properties such as the selection of dependent and independent variables, sound experimental design, and careful interpretation of the results. Specifically, PRT, speed, lateral lane position, SD of lane position and NASA-TLX were the dependent variables collected in their study which is in accord with the selection of measures for in-vehicle devices suggested by Green (1995). Dependent variables from other studies speak less directly to the relative safety of driver performance with a system.

The reviewed VES studies have included participant subjective ratings of visibility, glare, gap judgments, time-to-contact judgments, ease of use and mental workload, and objective measures of vehicle speed, lateral position, brake reaction responses, object detection and identification in the periphery. Continued use of these and other measures is endorsed. Varied methodologies and measures are required in efforts to obtain convergent results so that reliable evaluation of VES can be performed. Each study should, however, choose its focus, either to assess bottom-up (i.e., detection/recognition) or top-down (i.e., cognitive effects of system failure) processing. Otherwise confusion will result, especially if the two foci are incorporated into a loosely developed methodology.

A major limitation of both the reviewed simulator and field testing of VES has been the fidelity of the system and the external features it detects. The potential advantage of a VES is in the detection and response to human and animal hazards deemed critical to the primary task of safe driving. The purpose of a VES is not to enhance a central field of view to the driver. The purpose instead is to enhance only particular objects (e.g., pedestrians, other vehicles) within that range. This would, theoretically, enable the driver earlier detection and recognition, as a result of reduced search time. The implication is that those objects that do not differ in thermal energies from their backgrounds are not enhanced with the VES. If, instead, a VES were to fully enhance a section of the central view (i.e., 15° x 10°), then the task to the driver would be to not only detect and recognize critical objects through the entire windshield, but also within the enhanced image representation. This would result in the increased likelihood of captured attention in the enhanced section of the windshield and missed signals outside the enhanced central view (Ward & Parkes, 1994).

Finally, researchers have failed to address training issues and what a reliable sample size and appropriate selection method should be. Cited reports have not always been clear whether effective counter-balancing or random ordering techniques were used. There has also been the tendency to use inaccurate operational definitions in describing essential concepts in traffic safety. At present few studies have explicitly considered older driver experiences with VES. As product developers are focusing on making the sensors as inexpensive as possible for wider marketing and use, the onus is on researchers not only to evaluate these new products but to do it in a manner that contributes reliable and generalizable results.

A laboratory setting is highly artificial as it removes the participant from the actual driving environment. Certain cues, which cannot be included in low fidelity simulation research, are critical in the real world. For example, an important factor in detecting speed variability is the driver's interaction with the accelerator. A participant would be able to detect an increase in speed if they had pressed the accelerator down and were able to feel the pressure on their foot, through haptic feedback. Thus, they would not need to look at the HUD for this information in the real world as they would in a low fidelity simulator that did not provide such haptic information (see, e.g., Sojourner & Antin, 1990).

2.6 Present Study

Infrared VES appear to afford drivers with the ability to perceive low luminance contrast objects, which may reduce pedestrian accidents under reduced visibility conditions. While critical design issues for VES (see, Lunenfeld & Stephens, 1991; Parkes, Ward, & Bossi, 1995) and automobile HUDs (see, Gish & Staplin, 1995) have been articulated, experimental evaluations, which more adequately inform design, have progressed slowly (see, e.g., Caird & Chugh, 1997).

Human factors professionals have recognized the potential of VES and endorse assessment of how they influence safety and achieve their intended benefits (Lunenfeld & Stephens, 1991). The essential issue of VES is the degree to which drivers—especially those who are older with declining visual capabilities—are able to detect and use system information to control their vehicles safely. While these systems are touted to aid drivers during adverse (i.e., nighttime, fog, inclement weather) driving conditions, convergent and reliable experimental results are as yet unavailable. It is not known, for example, whether or not drivers will adopt higher speeds at night (a negative behavior compensation) because they can see further ahead. What and why a portion of the traffic environment should be enhanced should guide the selection and application of VES technology. Convergent empirical evidence for the safety and performance of these systems under a variety of simulated and real world contexts is needed (see, e.g., Caird et al., 1998). The purpose of this research project is to focus on which real world objects should be enhanced and how these enhancements impact of older and younger driver performance in important traffic contexts.

3.0 PRELIMINARY STUDY

3.1 Introduction and Hypotheses

A preliminary study (Horrey, 1999) was conducted that addressed the following two hypotheses:

- Conformal and non-conformal displays were expected to interfere with responses to surprising events.
- Responses to a highlighted pedestrian were expected to be faster, because detection would be improved.

3.2 Participants, Methods and Procedure

3.2.1 Participants. Thirty-two participants (16 men and 16 women) between the ages of 20 and 27 (M = 23) volunteered for the study. All drove, on average, 19,600 kilometers per year and had corrected or normal visual acuity and normal contrast sensitivity.

3.2.2 Video Driving Simulator. For this study, a video-based driving simulator was used which was composed of a vehicle mock-up, a projector, a projection screen, a computer, and digitized and modified road videos. The mock-up of a car consisted of a steering wheel, dashboard, and brake and accelerator pedals. Interactions with the brake and accelerator pedals affected the playback speed of the video. The size of the traffic video on the screen was 80 cm wide x 60 cm high and participants were seated approximately 350 cm from the screen. Traffic sequences were filmed from the viewpoint of the driver in a variety of urban and suburban settings. Most traffic footage used in the study was filmed on secondary or local suburban streets of Calgary where pedestrians would be expected. The sequences were then digitized at a 320 x 240 pixel resolution. Frame by frame development of conformal and non-conformal display imagery was performed in Adobe Photoshop™. Afterwards, each frame was integrated back into video footage in Adobe Premiere™. Traffic sequences were exported as QuickTime™ movies and compressed using the Intel Indeo™ R3.2 compression algorithm. Movies were also flattened and key framed at 30 frames per second for export to a Pentium™ PC. An Asymetrix Toolbook™

program was developed to coordinate the videos, and inputs and outputs to the driving simulator.

3.2.3 Conformal Display. Conformal imagery overlaps with and/or highlights visual features of the environment. A monochromatic bright green line was systematically applied to vehicles in the driving environment in accordance with the experimental design. Vehicles were highlighted if they 1) approached on the left, 2) were parked on the right, or 3) were parked on the left side of roads without a center line. For example, a green line appeared on the bumper of a vehicle at a fixed distance and continued to increase in size in accord with the speed with which the vehicle approached. Once the highlighted vehicle passed to the right or left it disappeared from sight. Horizontal visual angle of the enhancement when it appeared was 0.9° and 3.0° when it was closest to the driver. Figure 3.1 A illustrates the conformal display used in the study.

3.2.4 Non-conformal Display. A non-conformal display does not directly correspond with features in the external environment. A solid bright green circle which appeared at 3.1° below the visual horizon served as an analog display to approaching vehicles (see, e.g., Carel, 1961). As a vehicle came closer to the driver (i.e., on the right or left), the green circle expanded through 4 discrete sizes (0.5° to 1.3° of visual angle) until it disappeared when the vehicle disappeared. Thus, the non-conformal display gave general alerting information about the approach of a vehicle, but not information about the location of that vehicle. Figure 3.1 B illustrates the non-conformal display as an oncoming vehicle approaches. As the vehicle approaches, the green dot increases in size.

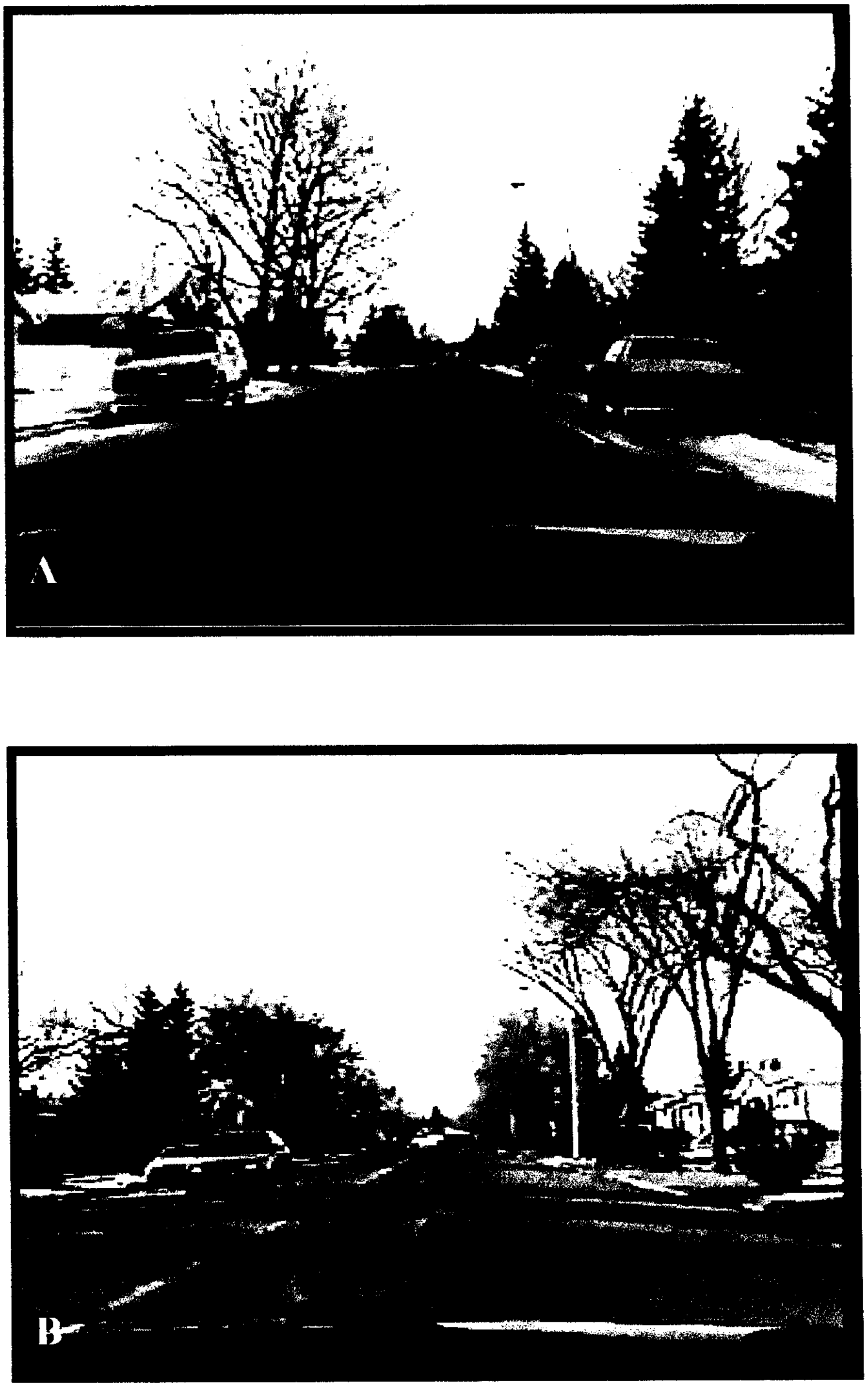

Figure 3.1. Conformal (A) and non-conformal (B) displays used in the preliminary experiment.

3.2.5 Procedure. After completing the consent form and tests for visual acuity and contrast sensitivity, participants filled out a background demographic and driving experience questionnaire. Participants were randomly assigned to one of the two display groups. As participants watched the film clips, they were instructed to drive as they ordinarily would and to decelerate and brake if a pedestrian or vehicle appeared that required a response. Participants could adopt three speeds as they drove through the video sequences. A practice block of traffic sequences was completed to familiarize participants with the functional limitations of the driving simulator, the tasks to be performed, and the display imagery. During the last film sequence of the practice block, a surprise event was given to all participants. A pedestrian appeared on the right, entered the roadway, and stopped. The task was to brake, to avoid hitting the pedestrian. Perception-response time was measured from the moment that the pedestrian appeared until the participant's foot touched the brake (see, Olson, 1996). During an experimental block of driving clips, four pedestrian surprise events were presented. Three of these pedestrians were similar to the practice block (standard event), while the fourth was highlighted (highlighted event). For this event, the pedestrian was highlighted with a vertical green line which increased in size during an approach (0.7° to 2.7° of visual angle). All of the events were counterbalanced for the study. Participants were given a post-experiment questionnaire and debriefed.

3.3 Results

The average baseline PRT to the pedestrian events was 1.4 s ($\underline{SD} = 0.3$) which for younger drivers falls into the higher percentiles of the young driver distribution (Olson and Sivak, 1986). Participants may have delayed their responses because they may not have been familiar with the experimental protocol or did not expect to strike the pedestrian given the available time. A main effect of event number ($\underline{F}(2,54) = 59.51$, $\underline{p} < 0.001$) was found which meant that responses to the three standard events improved from the first to the third occurrence. With more experience, participants became more prepared to brake to the appearance of the pedestrian. There were no differences between conformal and non-conformal display types or gender when responding to the appearance of a pedestrian.

PRTs for the highlighted pedestrian were significantly slower than for the standard pedestrian ($\underline{t}(23) = 4.595$, $\underline{p} < 0.001$). For the highlighted pedestrian, the effect of display type was significant (F(1,25) = 5.414, p = 0.03) on PRTs. PRTs for the conformal display were slower (M = 1.21 s, SD = 0.30) than the non-conformal display (M = 0.95 s, SD = 0.23). Twenty-five percent (4 of 16) of the participants in the conformal condition did not see the highlighted pedestrian, whereas, 13% (2 of 16) missed the pedestrian in the non-conformal condition.

During the debriefing, participants were asked which elements of the traffic system should be highlighted. Although many curious suggestions were made, the most common responses were to highlight traffic signs and pedestrians. The conditions when the display would be most effective were thought to be night and in inclement road conditions (e.g., fog and snow).

3.4 Discussion

This study demonstrated that previously not experienced enhancement of a pedestrian caused an increase in PRT. Several plausible interpretations can be made. First, the green enhancement of the highlighted pedestrian may have obscured the pedestrian. Until a pedestrian is recognized, the appropriate response cannot be made. Participants that missed the highlighted pedestrian mentioned that they were confused about how to respond. Thus, visual enhancement should not interfere with the recognition of important targets and hazards in the traffic environment. Second, coupling of rare or unexpected events to proper responses before they are needed in an emergency is a nontrivial problem.

Three guidelines are necessary for enhanced imagery to be useful to a driver: 1) it should increase the likelihood that pedestrians are detected; 2) highlighting should not interfere with object recognition; and 3) how to respond to the threat or hazard should be evident to the driver.

4.0 PRIMARY STUDY: METHODS

4.1 Participants

A set of pilot participants were used to debug software, refine the experimental protocol, and to test the time constraints of the scenarios. Ten participants (6 men and 4 women) were recruited from the University of Minnesota for pilot testing. They were all younger drivers (aged 19 to 32, $\underline{M} = 23.8$) and drove, on average 18,500 km per year (11,600 miles). The average corrected visual acuity for this group was 20/20 and all displayed normal contrast sensitivity. Pilot participants were paid $20 US for completing the study. Corrections to the scenarios, software and protocol were made based on their performance and feedback.

Forty-eight participants took part in the main study; half were younger drivers (aged 18 to 32, $\underline{M} = 23.5$) and half were older drivers (ages 67 to 86, $\underline{M} = 71.9$). Each age group had 24 participants, equally balanced between men and women. All had valid driver's licenses and drove, on average, 17,500 km per year (10,900 miles). Older participants drove an average of 3000 kilometers per year more than their younger counterparts. Appendix F gives a comprehensive description of each participant on a range of variables including age, acuity, and yearly exposure. Younger drivers were recruited using posters on the campus of the University of Minnesota. Seventeen younger drivers had corrective vision lenses. The average corrected visual acuity for this group was 20/20. All younger participants had normal contrast sensitivity. Older drivers volunteered from a number of community programs in the Twin Cities (e.g., the Elder Learning Institute, and the Elder Hostel Programs). Twenty older drivers had corrective vision lenses. The average corrected visual acuity for this group was 20/24 and all participants displayed acceptable levels of contrast sensitivity. Participants were required to score in the normal range for the Stereo Optics™ Sine Wave Contrast Test for no fewer than 3 of the 5 spatial frequency functions. All participants were paid $20 US for participating in the study.

Two older female participants declined to complete the study after experiencing motion sickness during the training trials. One older male withdrew after completing the baseline trials for the same reason. For some, motion sickness is an unfortunate side effect of driving in a simulator. All three that withdrew from the study were replaced with additional volunteers.

4.2 Materials

4.2.1 Simulator Hardware. This study was conducted using the flat-screen driving simulator at the Human Factors Research Laboratory at the University of Minnesota. Participants were seated in a 1989 Honda Accord LX situated in front of a 2.96 m wide by 2.2 m high Draper™ white screen. A NEC MultiSync™ MT 830+ data projector with a resolution of 800 x 600 pixels was used to project the driving simulation images. The simulation was run by a 250 MHz Silicon Graphics Indigo™ 2 computer with 128 MB of RAM. A Minolta CS-100 ChromaMeter™ was used to make photometric measurements of driving simulation elements which appear in Table 4.1 below.

4.2.2 Software and Modeled Environment Overview. Driving environments were created using Medit™ Version 2.1m (Open GL) 3D graphics software and LynX™ Version 3.2 development software. Four types of driving scenarios were developed for the study, each approximately 700 m to 1000 m long. In these scenarios, the road layout consisted of straight, bi-directional roads in city urban areas with one lane in each direction. Buildings, trees, open areas, and other vehicles were randomized across the scenarios. Presentation of other vehicles was at a rate of 10 per km of roadway (3 to 4 per km for moving vehicles and 6 to 7 per km for parked cars). Seven trials were developed to obtain baseline measures and did not include any VES imagery. Nine trials in day conditions with VES were developed as were 10 with varying levels of visibility in fog. Each of the scenarios or experimental trials is described in the Procedures section below.

4.2.3 Vision Enhancement Systems. Two types of VES were developed; one conformal and one non-conformal. Figure 4.1 A and C show conformal displays in daylight and fog, respectively. Figure 4.1 B and D show non-conformal displays. Both systems enhanced moving and parked vehicles and, in the intersection scenario, the traffic light.

Conformal vision enhancement of moving and parked vehicles consisted of a horizontal blue bar superimposed on the front and rear bumpers. As the vehicles approached, the blue bar increased in size (corresponding to the increasing size of the bumper). In the fog trials, the horizontal bar was seen at a greater distance than the vehicle itself. Table 4.1 lists the luminance ratio of various enhancement elements used in the study.

Non-conformal vision enhancement of moving and parked vehicles consisted of an expanding blue bar placed at 1.2° below the line of sight, directly in front of the driver. The expansion was coupled with the approach of the vehicle such that the size of the bar corresponded to size increases of the vehicle's bumper. The bar alerted the driver as to the approach of a vehicle but offered no visual cues as to the location of this vehicle (i.e., whether parked on the right, left, or oncoming). To use the non-conformal information, participants had to scan the environment for a corresponding object. The size in degrees of visual angle of the enhancements and vehicles in the study, can be found in Table 4.2 below.

In two scenarios (one for day and one for fog), the traffic light at the intersection was highlighted by the conformal and non-conformal VES. For the conformal condition, a blue bar was placed behind the traffic light such that it surrounded the light. For the non-conformal display, an expanding blue bar was placed on the road (identical to the bars placed for other vehicles) however, an image of a traffic light was superimposed on the bar thus denoting the approach to an intersection. The colour of the traffic light was not represented on the approaching bar (see Figure 4.1 D).

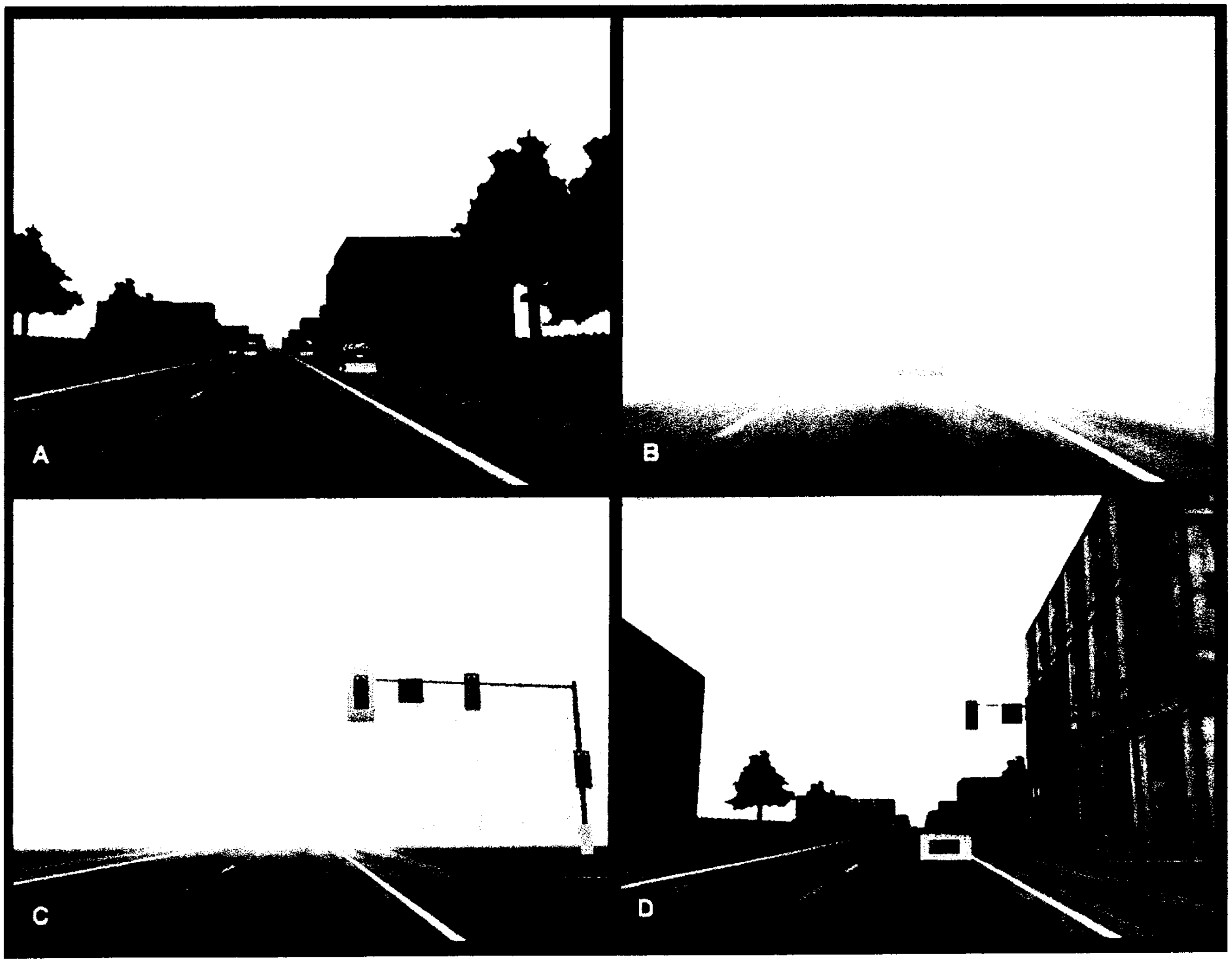

Figure 4.1. Examples of conformal (A and C) and non-conformal VES dislays (B and D). Conformal displays are overlaid directly onto traffic environment elements such as other vehicles (A) and stop lights (C). Non-conformal displays are coupled to the traffic elements such as other vehicles (B) and stop lights (D), but the information always appears centered on the roadway (B & D).

Table 4.1. Luminance contrast of certain driving simulation elements.

	Scenario	Element	Luminance Ratio[1]
1	All Day trials: Conformal	VES bar	0.33
2	All Day trials: Non-Conformal	VES bar	0.40
3	All Fog trials: Conformal	VES bar	1.28
4	All Fog trials: Non-Conformal	VES bar	1.46
5	Pedestrian: Day	Pedestrian	3.36
6	Pedestrian: Fog	Pedestrian	1.13
7	Intersection: Day	Amber light	0.95
8	Intersection: Day	Traffic light VES	1.20
9	Intersection: Fog	Amber light	1.18
10	Intersection: Fog	Traffic Light VES	1.62
11	Lead car: Day	Lead car	0.55
12	Lead car: Day	Brake lights	1.50
13	Lead car: Fog	Lead car	1.17
14	Lead car: Fog	Brake lights	1.13

Note: [1] Luminance ratio is the ratio between background luminance (in cd/m2) and the luminance of the element (in cd/m2). Background luminance represents the average of four measures taken on each side of an element. Element luminance was calculated by the average of 2 to 6 measures of an element depending on the size of the element.

4.3 Procedure

At the beginning of the 90 minute session, participants completed an informed consent form (see Appendix A) and a two page driving experience questionnaire (Appendix B). Visual acuity and contrast sensitivity were tested at a distance of 3 m using a Snellen Visual Acuity Chart and a Stereo Optics™ Sine Wave Contrast Test System, respectively. Participants were then seated in the driving simulator. Adjustments to the driver's seat were made to accommodate the size and preference of each participant. After adjustments, participants' eye position was contained in a headspace of 2.3 to 2.6 m from the white screen (M = 2.44) and 1.04 and 1.19 m from the floor (M = 1.12). Participants were given a short verbal overview of the study. Appendix D lists the complete verbal protocol that was used in the study. The participants completed two brief practice trials (without VES) in order to familiarize themselves with the dynamics of the simulator car (i.e., braking, acceleration, steering). Each of these trials lasted about four minutes. Participants were then randomly assigned to either the conformal or non-conformal condition.

Table 4.2. Angular subtense of elements in various scenarios.

	Scenario	Element	Initial θ[1] (in °)	Final θ (in °)	Comments
1	All trials: Conformal	VES bar (oncoming vehicles)	0.84 x 0.64	15.0 x 4.8	averaged across all vehicle types
2	All trials: Conformal	VES bar (parked vehicles)	0.84 x 0.64	7.1 x 2.3	averaged across all vehicle types
3	All trials: Non-Conformal	VES bar (oncoming & parked)	0.30 x 0.15	7.6 x 2.4	average across all vehicle types
4	All trials	Vehicle: Toyota 4 Runner	0.84 x 0.64	19.0 x 18.2	oncoming
5	All trials	Vehicle: Toyota 4 Runner	0.84 x 0.64	7.7 x 8.3	parked
6	All trials	Vehicle: VW Jetta	0.84 x 0.64	14.6 x 12.3	oncoming
7	All trials	Vehicle: VW Jetta	0.84 x 0.64	7.4 x 6.7	parked
8	All trials	Vehicle: Volvo	0.84 x 0.64	12.9 x 10.6	oncoming
9	All trials	Vehicle: Volvo	0.84 x 0.64	7.4 x 6.1	parked
10	All trials	Vehicle: Honda Accord	0.84 x 0.64	17.1 x 12.9	oncoming
11	All trials	Vehicle: Honda Accord	0.84 x 0.64	7.6 x 7.0	parked
12	All trials	Vehicle: Isuzu	0.84 x 0.64	17.4 x 18.4	oncoming
13	All trials	Vehicle: Isuzu	0.84 x 0.64	8.0 x 9.0	parked
14	Pedestrian: Day & Fog	Pedestrian	1.8 x 3.9	3.4 x 16.5	average across torso and stride
15	Lead car: Day & Fog	Lead car	1.8 x 1.3	–	at a distance of 49 m
16	Lead car: Day & Fog	Brake lights	0.44 x 0.30	–	at a distance of 49 m. measure is for one light only
17	Lead car: Day & Fog	Brake lights	0.15 x 0.10	2.7 x 1.5	initial at a distance of 125 m. final at a distance of 15 m.
18	Intersection	Amber light	0.24	–	diameter at change
19	Intersection	Amber light	1.94	–	height above Ss line of sight
20	Intersection	Red light	0.60	–	diameter at change
21	Intersection	Red light	10.0	–	height above Ss line of sight
22	All trials: Day	Horizon line	2.1		distance below Ss line of sight

Note: [1]Theta (θ) represents the visual angle of the object on the retina of the driver seated 244 cm from the projection screen. The numbers represented are in degrees of visual angle and are width and height, respectively.

Participants were instructed to drive as they normally would and to obey traffic rules. At the start of each scenario, participants were instructed to maintain a speed of either 35 mph (56 kph) for the everyday driving, intersection, pedestrian, and failure scenarios or 55 mph (88 kph) for the lead car scenarios. (Complete descriptions of these scenarios are found below.) They were asked to not exceed these speed limits. The participants were not told how to respond to traffic lights, lead cars, or pedestrians. The study consisted of three blocks of trials (baseline, day, and fog). The baseline block was completed first, followed by the day and fog block of trials. Participants could take a short break after each block if they desired.

All the scenarios within the three blocks were counterbalanced into four different trial orders. The baseline scenarios were performed in daytime conditions and did not include any VES imagery. Seven baseline scenarios were completed: four intersections (two light changes and two no light changes), two lead cars (one brake and one no brake), and one everyday driving scenario. During these trials, baseline measures of lane position, perception-response time (PRT), and response types (e.g., brake and/or steer) for the various events were recorded. PRT is defined as the time for drivers to detect and identify an event (e.g., pedestrian, light change), decide on an appropriate course of action, and to initiate the response (i.e., press the brake, steer away from the hazard) (Olson, 1996). Following the baseline session, participants were given several one-minute practice trials with either the conformal or non-conformal VES in day conditions, depending upon which condition they were assigned to.

After the practice trials, participants completed a series of experimental trials; three were intersections (two light change and one no light change), two lead cars (one brake and one no brake), one pedestrian, and one everyday driving scenario. In the fog session, participants were given two practice trials with either the conformal or non-conformal VES. Afterwards, participants were presented with seven fog scenarios: three intersections (two light changes and one no light change), two lead cars (one brake and one no brake), one pedestrian, and one everyday driving scenario.

4.3.1 Everyday Driving. Each of the scenarios is illustrated in Figure 4.2. Everyday driving is shown in panel C. The speed limit in this scenario was set at 35 mph (56 kph). Participants first drove past five vehicles parked on the right hand side (at varying distances apart) followed by five approaching vehicles in the oncoming lane. Vehicles were in similar locations during the fog session but visibility was reduced to 40 m. The reduced visibility was intended to mask the lane markings (i.e., center and shoulder line) thus making lane tracking more difficult.

4.3.2 Intersection. Four intersection scenarios were developed (see Figure 4.2 B). Each intersection trial required participants to approach at 35 mph (56 kph). The position of the intersection within the scenario was randomized. The intersection stop light was green as each participant approached. In two of the scenarios, the light did not change. In the other two scenarios, the light changed from green to yellow to red. The timing of the light allowed drivers to brake safely or, if they chose, to proceed through the intersection during a red light. The light change from green to yellow was triggered 83 m from the stop line of the intersection. At a posted speed of 35 mph, the duration of the yellow light was approximately 4 s which meets the requirements of the *Manual on Uniform Traffic Control Devices*. The change from yellow to red occurred at 20 m from the intersection. If participants did not stop for the light and continued through the intersection, the red light appeared for approximately 1.3 s before a participant entered the intersection. An acceptable time for the all-red interval of a traffic light is about 2.5 s (see, e.g., Billings, 1999; Senders, 1998). Thus, the present scenario made stopping for the lights at the intersection challenging. In one of the light change scenarios another vehicle approached the intersection at the same time as the participant's car. The forward movement of the other vehicle mirrored the participant's. The purpose of adding the other vehicle was to increase the visual workload of the situation. In the other light-change scenario, there was no oncoming vehicle at the intersection.

Figure 4.2. Traffic scenarios used in the study: A, follow the lead car and brake in a 2 s gap; B, respond to lights and intersection traffic appropriately; C, everyday driving through city streets; and D, the sudden appearance of a pedestrian which requires braking and steering to avoid.

In the fog conditions, the visibility of the intersection was reduced to 155 m. At this level, the light change to yellow could be perceived at a distance of 68 m to the intersection (see, e.g., Figure 4.1 C and 4.2 B). At a speed of 35 mph, the yellow light was visible for approximately 3 s. The visibility of the red light was the same as in the day conditions.

4.3.3 Pedestrian. The surprise appearance of a pedestrian was presented to measure a participant's ability to respond to an unexpected event (see Figure 4.2 D). The speed limit was 35 mph for the scenario. Along a stretch of road, with numerous vehicles parked on both sides of the roadway, a pedestrian suddenly appeared. Drivers had 35 m or approximately 2.3 s in which to respond (i.e., steer and/or brake). Once the pedestrian appeared it did not move, but did increase in size as it was approached (see Table 4.2 for visual angle information). For the fog session, visibility was reduced to 60 m. The pedestrian was slightly masked by the fog (see Table 4.1 for luminance ratio). However, it was clearly visible when it first appeared (see Figure 4.2 D).

4.3.4 Lead Car. In this scenario, participants followed another vehicle in their lane (see Figure 4.2 A). Two types of lead car scenarios were developed. In one, the lead car would brake at a set distance, while in the second, the lead car would continue uninterrupted throughout the trial. The speed limit was set at 55 mph (88 kph). At the start of a trial, the lead car was parked on the road, ahead of the participant's car. When the gap between the participant's car and the lead car decreased to 75 m the lead car started to accelerate to 35 mph (56 kph). In the braking scenarios, the lead car would start to brake either when the gap between the simulator car and lead car was 49 m or less, or when the lead car reached 850 m from the start of the scenario if the gap was not reduced to 49 m. Once the lead vehicle braked, it decelerated at a rate of 7 m/s^2. In the no brake scenarios, the lead car traveled at 35 mph regardless of the gap between the two vehicles. The size of the lead car (and the corresponding size of the brake lights) varied with gap distance (see Table 4.2). In the fog scenarios, visibility was set at a distance of 110 m. In this condition, the lead car was first visible at a distance of 63 m (see Figure 4.2 A). The lead car followed the same acceleration and deceleration patterns as in the day condition.

4.3.5 Failure Trials. At the conclusion of all experimental trials, participants were presented with a VES failure scenario. Visibility in the fog was set at 80 m for both the conformal and non-conformal failure trials. In the conformal VES failure trial, participants approached an intersection with a green light as an oncoming vehicle approached simultaneously. The VES bar, however, was misaligned. Instead of appearing superimposed on the bumper of the approaching vehicle, the VES bar appeared in the lane directly in front of the participant's car. The misaligned bar was visible from a great distance, but it was not clear which lane it was in until it was closer. The misaligned bar was not consistent with previous experiences, but may be indicative of the technical difficulties of aligning sensor and real-world information at the eye of the driver. In the non-conformal failure instead of the normal expansion of the bar as the vehicle approached, an oscillating figure-8 pattern appeared. An oscillating bar may represent a general sensor or cross-talk failure of the VES.

Participants then completed a short questionnaire that addressed the utility and preference for the VES as well as the realism and effects of the simulation (see Appendix C). They were then debriefed on the nature of the study, and remunerated for their participation.

5.0 PRIMARY STUDY: RESULTS

5.1 Experimental Design

The experimental design was a 2 (Age: Younger, Older) x 2 (VES Type: Conformal, Non-conformal) x 2 (Condition: Day, Fog). Each participant experienced baseline, day, and fog conditions. For all participants, the baseline session was completed first, followed by the day then the fog session. Half of the participants were in the conformal VES group and the other half were in the non-conformal VES group. Age and VES Type were between-subjects variables and Condition was a within-subjects variable. The use of baseline measures ensured that participants acted as their own control when comparing day and fog performances. Each of the scenario was analyzed separately (i.e., Everyday, Lead Vehicle, Pedestrian, Intersection, and VES Failure).

5.2 Everyday Driving

During this scenario, participants drove a section of roadway which varied in oncoming and parked vehicles. The dependent variable collected was lateral separation distance between the participant's vehicle and parked and oncoming vehicles. Whether conformal or non-conformal displays increased separation distance was of interest. The greatest separation distance was assumed to be at the point of passing a parked or oncoming vehicle (see, e.g., Summala, 1981a; 1981b).

For parked vehicles, a MANOVA for Gender (male, female), Condition (baseline, day, & fog), Age (young, old), and VES Type (conformal, non-conformal) found a significant Condition main effect ($F(2, 92) = 3.29$, $p < 0.041$). Age, VES Type, and Gender were not significant nor were there any interactions. Post hoc comparisons found differences between baseline and day ($p < 0.025$), and day and fog ($p < 0.037$). Day separation was less ($M = 1.51$ m) compared to baseline ($M = 1.61$ m), and fog ($M = 1.61$ m).

Oncoming vehicle separation from participant's vehicle was also tested with a MANOVA with the same between and within variables as parked. The VES Type by Condition interaction was significant, $F(2, 90) = 4.39$, $p < 0.015$. Age and gender were not significant. Figure 5.1 shows the means of baseline, day, and fog conditions for conformal and non-conformal displays. Those that used the conformal display kept a greater separation distance in day and fog conditions than those that used the non-conformal display.

5.3 Lead-Vehicle Braking

In the lead-vehicle braking scenario (see Figure 4.2A), the lead vehicle accelerated to 35 mph. Once a participants' vehicle was within 49 m, the lead vehicle braked at 7 m/s^2. If the participant did not eclipse the 49 m over the first 850 m of the course, the lead vehicle braked automatically. Individual participants may have had some lead-vehicle braking trials where they entered the 49 m window and others where they did not. This was especially true for the elderly and elderly women in particular. During the course of following the lead vehicle, some did not enter into the 49 m range.

If data was not complete for baseline, day and fog for each participant, their case was dropped from the MANOVA. Segregation of participant data into those that always entered the braking window and those that did not was not sufficient to increase cell n so that quantitative analyses were meaningful. A Condition main effect was significant ($\underline{F}(1,19) = 15.28$, $\underline{p} < 0.001$), with velocity at braking treated as a covariate. In general, baseline PRT's were slower than subsequent day and fog conditions. Other main effects, suffered from low n. Of the two car-following trials, one was a catch trial where they followed the lead vehicle throughout the trial, but it did not brake, whereas in the other trial it did. There was a slight tendency for those with the conformal VES to respond slightly faster then those with the non-conformal, but low n precludes a definitive quantitative test. In hindsight, tighter constraints on the car following time window and explicit goal setting to follow the lead vehicle in the verbal protocol are necessary to obtain quantitatively reliable data. From the qualitative data analyses (see 5.7 below), there is little doubt that highlighting lead vehicles in the fog is useful.

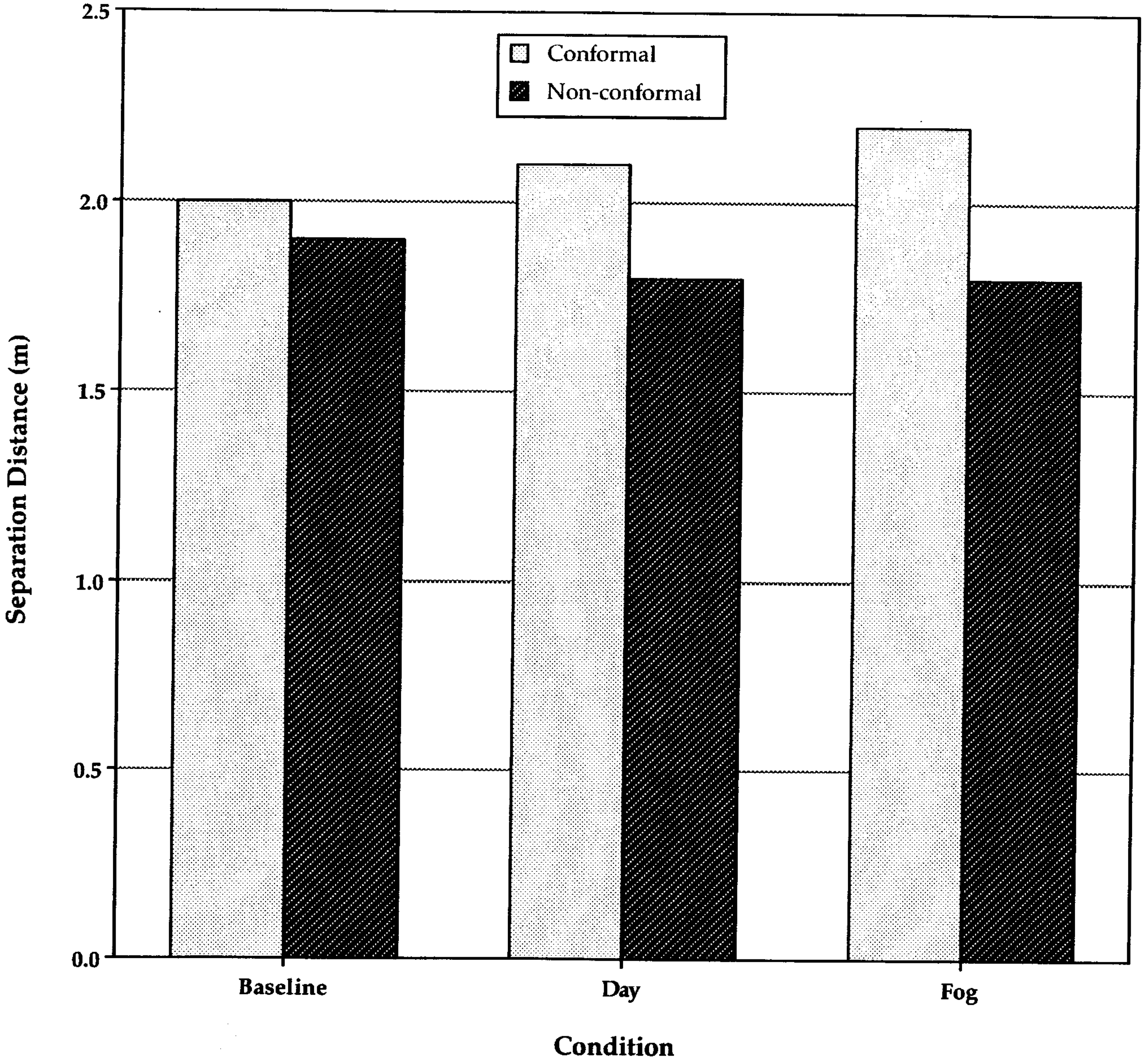

Figure 5.1. Separation distance to oncoming vehicles across baseline, day, and fog conditions for conformal and non-conformal VES displays.

5.4 Pedestrian Sudden Appearance

The sudden appearance of a pedestrian from between parked cars occurred twice; once in day and once in fog. The distance to the pedestrian was 35 m and at 35 mph this distance would be covered in 2.3 s. The most effective response was to brake and steer to avoid striking the pedestrian (see Figure 4.2 D). Response type and PRT were analyzed.

When the first pedestrian appeared during the day, 18 of 43 participants struck him. Seventeen of the 18 participants braked and one steered. Of those that did not strike the pedestrian, 17 steered and braked, and 8 steered only. Fewer participants struck the pedestrian in the fog (13) and again these drivers braked, but too late. Thirty-five avoided the pedestrian distributed across brake (16), steer (3), and brake and steer (16).

PRTs to the pedestrian, as indicated by either the first movement of the brake or steering wheel deflection, was faster when using the conformal display in day (*M* = 1.33 s, *SD* = 0.16) and fog (*M* = 1.51 s, *SD* = 0.31) than those that used the non-conformal display during the day (*M* = 1.48 s, *SD* = 0.18) or in fog (*M* = 1.73 s, *SD* = 0.62). A MANOVA for Age (young, old), Gender (male, female), VES Type (conformal, non-conformal), and Condition (day, fog) with velocity at the time the pedestrian first appeared as the covariate, found a significant effect for condition (*F*(1, 41) = 9.98, *p* < 0.003) and VES Type (*F*(1, 41) = 11.22, *p* < 0.002). Figure 5.2 illustrates these main effects. Age, gender, and interactions were not significant. PRTs in fog conditions were slower than during the day. PRTs to the pedestrian were faster with the conformal display than with the non-conformal display.

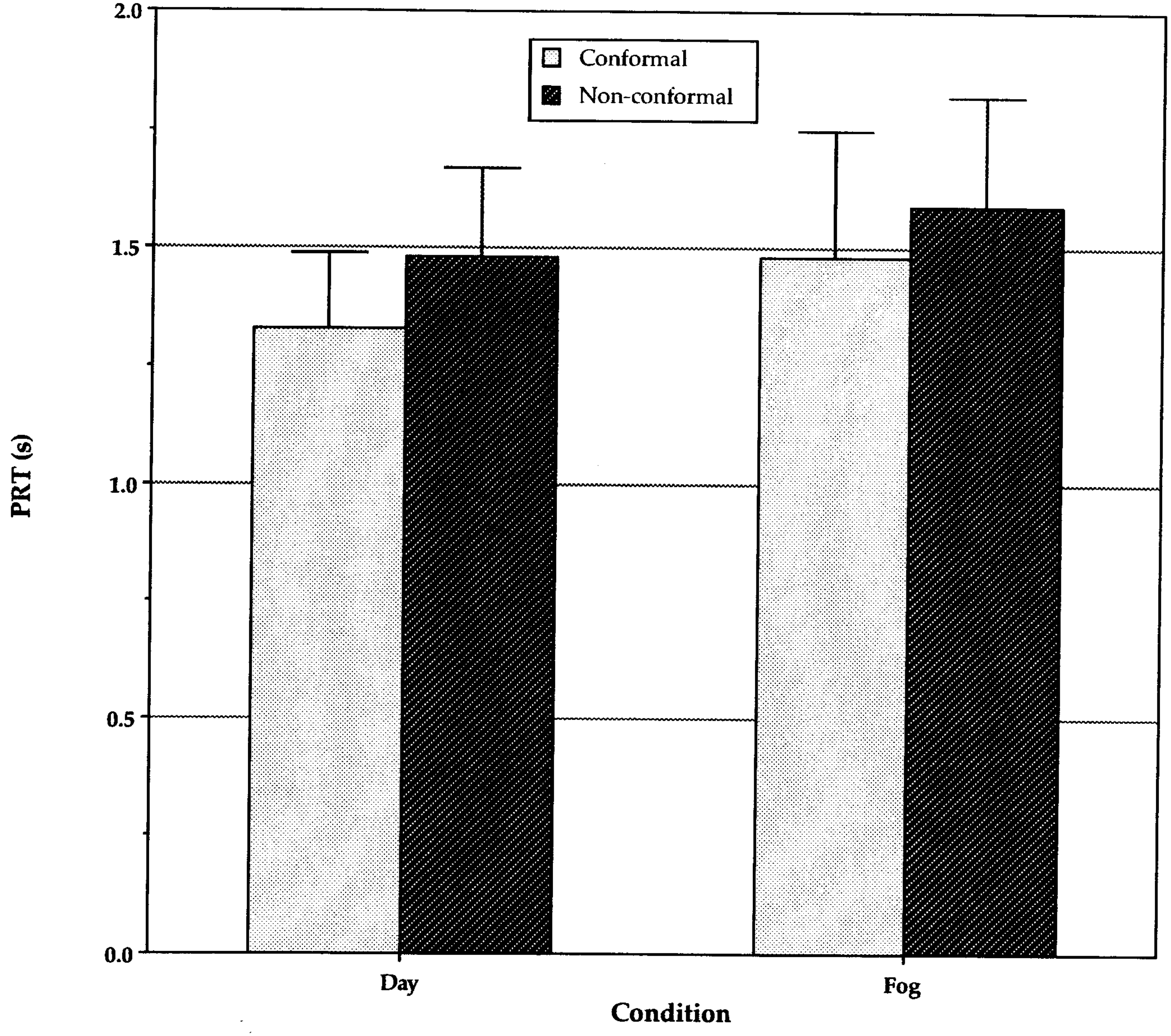

Figure 5.2. PRT to the sudden appearance of a pedestrian by condition for conformal and non-conformal VES displays. Error bars are one standard deviation.

5.5 Intersection Scenario

In the intersection scenario (see Figure 4.2 B), a participant approached an intersection and at 83 m the stoplight changed from green to yellow. At 40 m, the light changed from yellow to red. The yellow light interval at 35 mph was 4 s and the all-red interval was 1.3 s. This scenario, like the pedestrian scenario, was challenging. In the baseline condition, as a participant approached the intersection, a car was sometimes present. The forward movement of that vehicle mirrored the participant's vehicle. In the day and fog conditions, either the car was present in addition to the assigned display type (conformal, non-conformal) or no car was present and the stoplight was either enhanced conformally (see Figure 4.1 C) or non-conformally (see Figure 4.1 D). In the latter type of stoplight enhancement, the colour of the traffic signal was not indicated in the non-conformal HUD (see Figure 4.1 D). Fifty percent of intersection approaches were catch trials, that is, the light did not change and the driver proceeded through the intersection.

Approximately, two-thirds of participants ran the stoplight on the first and second baseline trials. During the day trials about half stopped and half ran the stoplight. In the fog, about two thirds stopped for the light. Initial velocity at the green to yellow and yellow to red changes were slower in fog. Within the stop or run the light responses, a number of trends are evident. More older drivers ran the stop light in day (13) and fog (10) than younger drivers in day (8) and fog (6). This may be due, in part, to slower response capabilities by the older sample. Those with the conformal display tended to run the light less often in day (8) and fog (5) than those that used a non-conformal display (day, 13; fog, 11). Additional scan time to determine what the non-conformal display was coupled to in the environment may account for having less time to stop for the traffic light and thus, more instances of running it. Finally, enhancement of the stoplight, either conformally or non-conformally, tended to benefit drivers in this condition. Because the stoplight appeared in the non-conformal display, search was minimized.

5.6 VES Failures

5.6.1 Conformal Failure. In the conformal failure, a blue bar approached the participant in the driver's lane which was coupled to an approaching vehicle in the left lane. Participant response types were the same for both older and younger drivers. The four possible response types were brake to a stop, brake and slow, no response, and brake and steer around. Ten participants braked to a stop and two braked and steered around the bar in their lane in each age group. The most common response was to brake to a stop, because the approaching blue bar was perceived as a threat.

5.6.2 Non-conformal Failure. Younger and older age groups had similar response patterns to the non-conformal display failure which oscillated in a figure-8 pattern on the roadway. The most frequent response was no response (14/24). Less frequent responses included brake to a stop (5), brake and slow (4), and brake and steer around (1). The oscillating display, unlike the conformal failure, did not indicate a pending collision and was ignored by many. Participants were probably confused as how to respond.

5.7 Qualitative Analyses

After an initial examination of the responses to the Post Experiment Questionnaire (see Appendix C), six open-ended questions were analyzed in depth (#'s 24, 28, 29, 30, 50a, 50b). These questions addressed positive and negative perceptions of the conformal and non-conformal VES. A compilation of the written responses to the six questions can be found in Appendix G. Patterns of responses are presented here.

Self reports of the fidelity and realism of the fog seems to support that the fog used in the primary experiment was adequate. When asked whether the VES helped them to notice hazards, both younger and older drivers responded that both types of VES systems made them more aware of other vehicles, but not necessarily to unexpected hazards such as pedestrians. In general, older drivers appeared to be somewhat more skeptical of the utility of VES than younger participants. When asked whether VES interfered with their ability to respond to hazards, participants mentioned that the pedestrian may not have been noticed as quickly because attention was focused on the enhancements. For those that experienced the non-conformal VES, a number wrote that the display obscured a portion of the roadway. Focus on the enhancements may reduce the use of perceptual cues such as the outline of vehicles. A reduction in scene scanning was also mentioned.

Questions 3 and 4 asked what participants liked and disliked about the VES respectively. Positive comments included: assistance in fog; felt safer (conformal); highlighted the traffic light; and helped to know where other vehicles were. Negative comments or dislikes included: distracting when many vehicles were present (conformal); makes a driver only look out for cars; did not show pedestrians; did not show where vehicles were (non-conformal); and too much effort to match bars to cars (non-conformal).

The final pair of questions asked which traffic situations would benefit from enhancements and which would not. When environmental conditions restricted visibility, such as night, snow, fog, and rain, VES was thought to be advantageous. Locations where it may benefit included: intersections, railway crossings, parked vehicles that were running, and during rural driving. Extremely heavy traffic and cluttered environments were thought to be poor situations for the application of VES. Daytime driving, which was a phase of the testing regimen, was also thought to be a place where VES may decrease driving performance.

6.0 DISCUSSION AND CONCLUSIONS

6.1 Experimental Results

The reported research studies tested conformal and non-conformal VES displays during the day and in fog with younger and older drivers. Separation distance to oncoming vehicles was greater in the conformal condition than the non-conformal condition. This increased separation is a positive benefit (especially in fog) because it allows for larger safety gap between the drivers' vehicle and other road users (thereby allowing them more room to maneuver in the event of an emergency). In the day and fog conditions, responses to the sudden appearance of the pedestrian were faster for the conformal display than the non-conformal display. The presence of the non-conformal bar in a central location may have inadvertently, made the task of detecting the pedestrian more difficult. The pedestrian appears in close proximity to the non-conformal VES bar. The bar may have therefore visually masked the pedestrian. Highlighting the stoplight reduced the need to scan the environment for the link between the display information and environment information. Certain types of technical problems such as the reliability of conformal systems may cause drivers to stop when they need not, if highlighting information is not attached to intended objects.

Subjective impressions of the conformal and non-conformal systems, once experienced, were quite interesting. The perceived benefits of VES systems are in situations where visibility is limited by either weather (e.g., fog, snow, rain), time of day (e.g., nighttime, dusk) or roadway geometry (e.g., curves, railway crossings). VES devices may distract—especially when unexpected events occur. Less than one-quarter of participants said they would use a VES with regularity if it were installed in their vehicle. Although separation distance increased when oncoming vehicles were highlighted with a conformal bar, enhancement of parked and oncoming vehicles was thought to be of questionable usefulness.

Overall, conformal displays can clutter the traffic environment with blue bars which may distract drivers. Non-conformal displays require the driver to scan the environment for the link between displayed and environmental objects. In settings where boredom may prevail, this may increase vigilance. However, in congested heavy traffic, the highlighting information may add to the visual workload. Conformal displays provide enhancements in the spatial location where needed. Non-conformal displays heighten awareness of approaching objects.

With the exception of the intersection scenario, age differences between younger and older drivers were not found in the quantitative analyses. Older drivers are known to have difficulties with intersections (Caird & Hancock, in press) and tend to have higher accident involvement (Massie, et al., 1995). The absence of statistical differences between age groups, we believe, should be interpreted as a positive result. The sample of older drivers in the primary study were active physically and mentally. Of course increasing the number of participants over the age of 75, could reveal a number of age differences that were not indicated in the present study. Although the studies did not address night driving, future studies that do may want to include a larger sample of older drivers that do not drive at night. Only 2 of 24 older drivers in the study agreed or strongly agreed with the statement that they do not drive at night.

6.2 Conclusions

Ideally, a VES forewarns the driver of changes in road geometry and the presence of potential hazards such as pedestrians and animals on or near the road. Once illustrated using salient visual cues, a driver reacts appropriately and proceeds safely. Pragmatically, these goals are not so easily achieved (Barham, et al., 1999; Wierwille, 1993). Coupling or overlaying of visual cues onto the roadway or pedestrians is limited by technical and driver constraints. When a visual cue is placed over an environmental cue to increase the contrast and salience of that cue, the environmental cue may then be obscured. In addition, a highlighted cue is then increased in relative importance over others. Highlighting may be insufficient to allow a driver to identify an object and react appropriately. The additional processing necessary to achieve recognition may exceed the additional detection time had the object not been highlighted. Basic human limitations constrain performance with each type of enhancement. Response time increases and decreases are possible depending on signal detection, signal confusion, distraction, and response selection. If additional clarification of a signal is required by a driver to identify a hazard, response time may not be optimal. If presentation of visual enhancements is consistent for a long period of time, response selection with each becomes more efficient.

Enhancing the salience of certain visual cues, such as oncoming and parked vehicles, may reorder and restrict the prioritization and search for more important cues (Neibur & Koch, 1998). Perceptual and response experience with a system is necessary before the highlighting of new cues achieves an appropriate level of performance. If VES systems are operated only at night or in limited visibility conditions, acquiring sufficient experience may be an issue. Specific highlighting of an object, over others, implies that the object is of recognized importance by traffic safety experts. Treatment of the environment with retroreflective material indicates the importance of edgelines, centerlines, stoplines, signs, and pedestrian clothing to vehicle control, hazard detection, and traffic control adherence (Triggs & Fildes, 1986). VES may provide information that is redundant, replaces, enhances, or is non-essential. The placement of the information within the vehicle, in the environment, or both logically follows. Each kind of enhancement has advantages and disadvantages and the relative effectiveness of each to increase mobility and safety is rarely known.

6.3 Limitations of Present Research.

Experimental design trade-offs limited specific comparisons that could be made. In particular, the set ordering of baseline, day, and fog may have introduced order or learning effects. A fog baseline condition against which to compare fog performance would have been beneficial. The decision to not have a fog baseline was made because participants would have had to come back for a second session. Unfortunately, this was not logistically or economically feasible. Allowing participants to drive as they would ordinarily made data reduction, classification of behaviours, and analysis problematic. Analysis of the car following and intersection scenarios was limited as a result. The use of scenarios for testing performance in specific contexts was relatively effective (Schiff & Arnone, 1995) and achieved a greater degree of ecological validity. However, constraints to a scenario such that fewer choices are available would significantly increase the statistical power of certain comparisons. In the future, scenarios should be constrained so that quantifiable behaviours can be extracted.

Simulation of nighttime and snow conditions is exceedingly difficult to achieve in a driving simulator due to luminance limitations of projection systems and the computational burdens of snow. Simulation of differential wheel traction is also computationally intensive. Fog is relatively easy to model graphically.

6.4 Future Research

Like many human factors research endeavors, long term use of a technology was limited in this study (see, e.g., Chapanis, 1988). Long term adaptation to a VES display would, hypothetically, allow older drivers to perceptually learn the salience of visual enhancements. Similarly, when to use the system could be learned. If VES devices were installed into a driver's own vehicle for a prolonged period of time, strategic uses could be observed (see, e.g., Francher, et al., 1998). Increases in driver speed above previous levels on routine routes could be determined (i.e., to determine behavioural adaptation) (Caird, in press; OECD, 1990). The use of VES to achieve ends are not in the best safety interests of the driver (Moray, 1976).

A number of the conformal enhancements made in the present study are not technically possible at this time. What should be enhanced is a crucial question. How can highlighted information be coupled to existing responses without interference? Is detection less likely, in the presence of enhancements, when unexpected events occur? These are critical questions that must be addressed in the design of VES. Specification of enhancement that is meaningful to the driver and can be integrated into a repertoire of actions, and is technically feasible should determine the direction of research and development as opposed to brute technology infusion into the driver's cockpit.

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8.0 APPENDICES

8.1 Appendix A: Informed Consent

UNIVERSITY OF MINNESOTA: INFORMED CONSENT FORM

The Effects of Vision Enhancement Systems on Older Drivers

Investigator: **Peter Hancock. Peter is the Director of Research at the Human Factors Research Laboratory.**

This consent form is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully.

You are invited to participate in a research study investigating driving performance in a computer-generated driving environment. You were selected because you are within the age range needed for the study and you have a valid driver's license.

Background Information: The purpose of this study is to collect measures of driver behavior, fatigue, and attention while using a vision enhancement system in simulated roadway environments.

Procedures: If you agree to participate in the study, you will be asked to take several visual tests, drive the driving simulator, and fill out some questionnaires about your driving background and experiences with the driving simulator. For the driving simulator, images of traffic environments will be projected onto a screen in front of the simulator and you will be able to drive your vehicle through them. You will be required to participate in a single driving session that will last about 90 minutes.

Risks: There is a possibility that you will experience motion sickness while driving in the simulator. This is only likely for those individuals who regularly get car or plane sick. If at anytime you do not want to proceed as a participant in this study, you are free to indicate to the experimenter that you would like to leave. Throughout the study, you will be able to take breaks.

Compensation: Upon successful completion of the experimental criteria, you will be awarded $20 at the end of the session.

Confidentiality: All information you provide will kept confidential. In any sort of report we might publish, we will not include any information that will make it possible to identify you. Research records will be kept in a locked file; only researchers will have access to the records.

Voluntary Nature of Study: Your decision to participate in this study will in no way affect your current or future relations with the University of Minnesota. If you decide to participate, you are free to withdraw at any time without affecting those relationships.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate. In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to not answer specific items or questions in interviews or on questionnaires. You are free to withdraw from the study at any time without penalty. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact:

Dr. Peter Hancock, University of Minnesota
Phone: (612) 626-7521, peter@hfrl.umn.edu

If you have any questions concerning your participation in this project, you may also contact the Research Subjects' Advocate Line, D528 Mayo, 420 Delaware Street SE, Minneapolis, MN 55455. The phone number is (612) 625-1650.

Participant	Date
Investigator	Date

A copy of this consent form has been given to you to keep for your records and reference. This research has the ethical approval of the Institutional Review Board: Human Subjects Committee.

8.2 Appendix B: Driving Experience Questionnaire

Participant # ____________ Age __________ Gender____________

1. Do you have a valid Driver's License? Yes No

2. How many years have you had a Driver's License?

3. About how many miles per year do you drive? _______ miles / year

4. How many moving violations have you had in the last two years?

5. Have you had any accidents where either yourself or another driver was responsible?

Yes No

Use the following scale to respond to questions 4 through 7.

1	2	3	4	5
Never	1-2 times a year	1-2 times a month	1-2 times a week	Everyday

6. How often do you drive?	1	2	3	4	5
7. How often do you drive on city streets?	1	2	3	4	5
8. How often do you drive on rural / country roads?	1	2	3	4	5
9. How often do you drive on freeways?	1	2	3	4	5

10. Do you wear glasses or contact lenses that correct your vision while driving?
Yes No

11. If so, are they bifocals? Yes No

Trifocals? Yes No

12. Do you have any diseases or degeneration in your eyes? Yes No

If yes, please specify:

13. Are you using prescription medications that you have been told will affect your driving? Yes No

14. Do you ever experience motion sickness (i.e., car sick or sea sick)?
Yes No

15. Have you driven a vehicle with a head-up display or a vision enhancement system? Yes No

Use the following table to respond to questions 16 through 23.

1	2	3	4	5
Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree

16. I always know how to act in traffic.	1	2	3	4	5
17. I never regret my decisions in traffic.	1	2	3	4	5
18. I don't care what other drivers think of me.	1	2	3	4	5
19. I always remain calm and rational in traffic.	1	2	3	4	5
20. Glare from oncoming headlights at night bothers me.	1	2	3	4	5
21. At times, I have difficulty judging the speed of my vehicle.	1	2	3	4	5
22. I do not drive at night.	1	2	3	4	5
23. I usually avoid rush hour driving.	1	2	3	4	5

Visual health tests (for experimenter testing):

Visual acuity 20/____

Contrast sensitivity A___ B___ C___ D___ E___

8.3 Appendix C: Post-Experiment Questionnaire

Participant # ___________

<u>Please answer all questions</u>.

24. How realistic was the fog that was used in the simulation?

1	2	3	4	5
Not at all like real fog				Exactly like real fog

24. Did you have any difficulties with any of the scenarios (e.g., stopping in time)?

Yes No

If yes, please describe:

25. Was the choice of color for vehicle enhancement appropriate? Yes No

Why or why not?

26. Were the vehicle enhancements more beneficial to you in the day or in the fog?

Day Fog Same

Please explain?

27. Did the vision enhancements help you to notice hazards? Yes No

Please explain?

28. Did the enhancement of vehicles interfere with your ability to respond to hazards?

Yes No

If so, describe what happened and under what conditions?

29. What other traffic situations or conditions do you think that vision enhancement would benefit?

30. What other traffic situations or conditions do you think that vision enhancement
would be disadvantageous?

31. If you had this vision enhancement system operating in your car, how often would
you use it?

1	2	3	4	5
Never	Rarely	Occasionally	Often	Always

32. Would you be willing to pay extra to have it installed as an option in a new car?

Yes No

If yes, how much would you be willing to spend? $ __________

Use the following scale to respond to questions 34 through 41.

If you were in a hurry to get to an important appointment how often would you (remember there are no right or wrong answers):

1	2	3	4	5
Never	Rarely	Occasionally	Often	Always

34. Run a red light to get to the appointment sooner	1	2	3	4	5
35. Drive at 5-15 mph over the speed limit	1	2	3	4	5
36. Drive around lowered gates at a railway crossing	1	2	3	4	5
37. Speed in a school zone on a Saturday	1	2	3	4	5
38. Do a rolling stop through a stop sign (i.e., not a complete stop)	1	2	3	4	5
39. Tailgate other people to get them to drive faster	1	2	3	4	5
40. Get angry at other drivers for being in your way	1	2	3	4	5
41. Talk on the cellular phone	1	2	3	4	5

Use the following scale to respond to questions 42 through 47.

1	2	3	4	5
Never	Rarely	Occasionally	Often	Always

42. I felt nauseous in the driving simulator.	1	2	3	4	5
43. The driving simulator allowed me to brake appropriately.	1	2	3	4	5
44. The gas pedal and brake in the simulator allowed me to adequately control my speed.	1	2	3	4	5
45. The steering of the driving simulator allowed me to make maneuvers correctly.	1	2	3	4	5
46. The speeds that I drove at were unsafe.	1	2	3	4	5
47. The speeds that I drove at were appropriate for the conditions.	1	2	3	4	5

Did your driving speed increase or decrease with the vision enhancement?

48. In the day, I drove:	faster.	slower.	the same speed.
49. In the fog, I drove:	faster.	slower.	the same speed.

50. List 3 things you liked about the vision enhancement display that you used and 3 things that you disliked about it.

Liked	Disliked
1.	1.
2.	2.
3.	3.

Thank you very much for your time and effort!

8.4 Appendix D: Experiment Protocol

Thank you very much for coming here to participate in this experiment.

Give informed consent form, pre-experiment questionnaire, test for visual acuity and contrast sensitivity.

> *If visual acuity is below 20/30 and 2 of the 5 functions in the contrast sensitivity chart are below normal then the recruit does not participate.*
>
> *If visual acuity is below 20/40 then the recruit does not participate.*
>
> *If contrast sensitivity is consistently below the normal function then the recruit does not participate.*

Please take a seat in this vehicle. You can move the seat to suit your comfort.

Are you comfortable in your seat? Try pressing the accelerator and brake. Can you reach them comfortably?

Today you will drive through a simulated environment just as you would in the real world. This simulated environment is generated by the computers you see around you, and projected onto the screen in front of you.

You can use the brake and the accelerator to control the rate at which you drive through the simulation. If you press the accelerator your car will speed up, and if you press the brake your car will slow down. You can turn the steering wheel to change lanes or drive around curves.

Do you have any questions?

Now we are going to give you some practice with using the steering wheel, the brake, and the accelerator.

At first you may experience some difficulties in controlling the vehicle. This is normal. As we proceed through the practice session your performance will improve. The goal is to practice driving in the simulation until you demonstrate you can safely and comfortably control the vehicle.

If at any time you feel uncomfortable please let me know and we can take a break. Are you ready? *If yes, then start training session.*

Goal of practice is to get participants used to the steering, brake and accelerator.

TRAINING SESSION

Start Training 1

This is a one-way highway in a rural area. We are going to use this road for practice. I would like you to...

<u>Tasks for Training 1</u>:

1. Accelerate this vehicle to 25 mph
2. Step on the brake until the vehicle comes to a complete stop
3. Accelerate to 35 mph
4. Now maintain that speed
5. Move the vehicle to the left lane
6. Increase your speed to 55 mph
7. Now decrease your speed to 35 mph
8. Move to the right lane
9. Step on the brake and bring the vehicle to a complete stop

End session. Begin Training 2 session.

<u>Tasks for Training 2</u>:

1. Accelerate to 35 mph
2. Maintain your speed and control of the vehicle as you move through the turns

(Repeat practice session if deemed necessary i.e., if the participant is swerving extensively or having difficulty maintaining control of the vehicle.)

"Do you feel comfortable in controlling the vehicle in the simulation?"

If yes, then proceed to Baseline session.

BASELINE SESSION PROTOCOL

Now that you have had practice in controlling the simulator vehicle, you are going to drive through several different traffic scenarios. Each scenario lasts about 1 minute. As you drive through the simulation, you should follow normal traffic rules. Respond to traffic situations, as you normally would while driving. **I will tell you the speed limit for each scenario before it begins. The speed limit will be either 35 mph or 55 mph.**

Do you have any questions?

Begin baseline session. (all scenarios are counterbalanced into orders)

The speed limit for the next scenario is (35/55) mph. Please stay close to this speed throughout the trial. *(repeat for each of the 7 scenarios)*

End baseline. Offer participants a break before proceeding with day session.

Assign participant to one of two VES display conditions: (a) Conformal, (b) Non-conformal.

VES DAY SESSION PROTOCOL

FOR CONFORMAL CONDITION:

A new vision enhancement system has been developed that detects other vehicles on the roadway and places a blue bar on the front and rear bumpers of the vehicles. Today, we are going to test how this system works.

The blue bar will appear on the screen but is not part of the vehicles in the roadway, rather it is intended to appear on the windshield. The blue bar thus enhances the appearance of other vehicles in the roadway.

Do you have any questions?

Here are two practice trials so you can familiarize yourself with the vision enhancement system. *(run Day: Practice 1 & 2)*

As you can see, the blue bar appears on top of the front and rear vehicle bumpers. As the vehicles get closer, the blue bar increases in size.

Now that you've seen the system, do you have any questions?

FOR NON-CONFORMAL CONDITION:

A new vision enhancement system has been developed that detects other vehicles on the roadway. It will display information on the screen right in front of you slightly below your line of sight. It is not part of the external environment, and is intended to appear on the windshield. Today, we are going to test how this system works.

The image is a horizontal blue bar that will appear on the screen when other vehicles are nearby and it will expand as they approach.

Do you have any questions?

Run Day: Practice 1 & 2.

As you can see the blue bar appears slightly below line of sight and is not part of the external environment.

Now that you have seen the system, do you have any questions?

FOR BOTH CONDITIONS:

Do you understand how the vision enhancement system works? Are you comfortable with it?

Now you are going to drive through several different traffic scenarios while using this vision enhancement system. Again, each scenario lasts about 1 minute. As you drive through the simulation, you should follow normal traffic rules. Respond to traffic situations, as you normally would while driving. **I will tell you the speed limit for each scenario before it begins. The speed limit will be either 35 mph or 55 mph.**

Do you have any questions?

Begin Day session. At the end, offer participants a short break before proceeding with the Fog session.

VES FOG SESSION PROTOCOL

BOTH CONDITIONS

Now we are going to test the same vision enhancement system in foggy conditions. First, I will show you a few practice trials to familiarize yourself with the fog and the vision enhancement system.

Run Fog: Practice 1 & 2.
Do you have any questions?

Now, you are going to drive through several different traffic scenarios in foggy conditions while using this vision enhancement system. Again, each scenario lasts about 1 minute. As you drive through the simulation, you should follow normal traffic rules. Respond to traffic situations, as you normally would while driving. **I will tell you the speed limit for each scenario before it begins. The speed limit will be 35 mph or 55 mph.**

Do you have any questions?

Begin Fog session.

Following Fog session, return to conference room. Offer participants a chance to get a drink of water or to use the washroom.

Give participants final questionnaire, debrief, answer questions, and pay them for their participation.

Make sure post-simulation time lasts 10 to 15 minutes to allow participants to readjust to real, non-simulated world.

8.5 Appendix E: Post-experiment Debriefing

VES Experiment

Thank you very much for your participation, your assistance has helped us.

A vision enhancement system (VES) is an application of Intelligent Transportation System (ITS) technology. The goal of this system is to reduce automobile accidents (especially in adverse weather and road conditions) as well as to increase the mobility of older drivers (who tend not to drive under these conditions).

The purpose of the current study was to assess the effects of different vision enhancement systems on the driving behavior of younger and older adult drivers in different traffic situations. This driving behavior was measured in terms of brake, accelerator and steering wheel responses throughout the experimental trials. These measures of behavior will allow the researchers to investigate the benefits and detriments of using such a vision enhancement system and therefore inform the design of these systems.

You are welcome to contact us for results or any other information you want regarding this study.

You may contact:

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Director of Research, Human Factors Research Laboratory
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If you are interested in learning more about VES, ITS, older driver programs, or other transportation human factors issues, the following web site offers numerous links:

http://www.acs.ucalgary.ca/~erg/its/tc.htm

8.6 Appendix F: Participant Descriptions

Younger Participants

Participant Number	Age	Gender	VES Type	Km Driven per Year	Acuity	Drive at Night?[1]	Likely to Use a VES?[2]	Pedestrian PRT (s)[3]
M1	20	M	Conformal	12000	20/20	1	4	1.45
M2	24	M	Non-Conf	16000	20/20	1	2	1.42
M3	20	M	Conformal	-	20/20	4	2	1.57
M4	32	M	Non-Conf	32000	20/20	2	1	1.25
M5	32	M	Conformal	16000	20/20	1	3	1.16
M6	20	M	Non-Conf	1600	20/20	2	3	1.35
M7	23	M	Conformal	4800	20/20	1	2	1.24
M8	22	M	Non-Conf	20800	20/20	1	3	1.99
M9	20	M	Conformal	16000	20/20	1	4	1.54
M10	19	M	Non-Conf	16000	20/20	1	2	1.62
M11	27	M	Conformal	32000	20/20	1	4	1.34
M12	19	M	Non-Conf	11200	20/20	1	3	1.52
F1	20	F	Conformal	1600	20/20	2	3	1.44
F2	29	F	Non-Conf	800	20/20	1	2	1.47
F3	20	F	Conformal	4000	20/20	1	3	1.30
F4	27	F	Non-Conf	40000	20/20	1	3	1.26
F5	32	F	Conformal	12800	20/20	2	3	1.25
F6	18	F	Non-Conf	1600	20/20	2	3	1.67
F7	21	F	Conformal	24000	20/20	1	3	1.43
F8	24	F	Non-Conf	28800	20/20	1	3	1.77
F9	24	F	Conformal	24000	20/20	1	3	1.36
F10	19	F	Non-Conf	-	20/20	1	3	1.83
F11	21	F	Conformal	19200	20/20	1	3	1.14
F12	22	F	Non-Conf	40000	20/20	1	4	1.76

Notes: [1]I do not drive at night. (Likert scale: 1- strongly disagree, 2- disagree, 3- neither agree nor disagree, 4-agree, 5- strongly agree). [2]If you had this VES operating in your car, how often would you use it? (Likert scale: 1- never, 2- rarely, 3- occasionally, 4- often, 5- always). [3]Perception-response time to the initial appearance of the pedestrian in day.

Older Participants

Participant Number	Age	Gender	VES Type	Km Driven per Year	Acuity	Drive at Night?[1]	Likely to Use a VES?[2]	Pedestrian PRT (s)[3]
OM2	76	M	Non-Conf	19200	20/20	1	4	1.73
OM3	72	M	Conformal	32000	20/26	1	3	1.19
OM4	72	M	Non-Conf	24000	20/25	3	2	-
OM5	69	M	Conformal	12800	20/20	1	3	1.20
OM6	71	M	Non-Conf	19200	20/26	2	1	1.50
OM7	72	M	Conformal	16000	20/26	2	3	1.41
OM8	68	M	Non-Conf	24000	20/20	2	3	1.54
OM9	71	M	Conformal	24000	20/20	1	3	1.50
OM10	69	M	Non-Conf	19200	20/20	1	3	1.25
OM11	77	M	Conformal	28800	20/23	2	4	1.30
OM12	73	M	Non-Conf	19200	20/30	2	3	1.68
OM13	86	M	Conformal	8000		2	4	1.39
OF1	68	F	Conformal	16000	20/25	1	2	1.55
OF2	67	F	Non-Conf	16000	20/25	2	2	1.47
OF3	78	F	Conformal	4800	20/40	2	-	1.10
OF4	74	F	Non-Conf	17600	20/25	4	3	1.51
OF5	69	F	Conformal	16000	20/20	1	3	1.24
OF6	68	F	Non-Conf	9600	20/20	1	2	1.51
OF7	68	F	Conformal	24000	20/23	2	3	1.52
OF8	69	F	Non-Conf	-	20/25	3	3	1.52
OF9	79	F	Conformal	800	20/25	5	4	1.44
OF10	67	F	Non-Conf	-	20/30	2	2	1.41
OF11	71	F	Conformal	12800	20/26	2	5	1.70
OF12	72	F	Non-Conf	20800	20/20	2	1	1.61

Notes: [1] I do not drive at night. (Likert scale: 1- strongly disagree, 2- disagree, 3- neither agree nor disagree, 4-agree, 5- strongly agree). [2] If you had this VES operating in your car, how often would you use it? (Likert scale: 1- never, 2- rarely, 3- occasionally, 4- often, 5- always). [3] Perception-response time to the initial appearance of the pedestrian in day.

8.7 Appendix G: Open-Ended Questionnaire Responses

1. Did the vision enhancement help you notice hazards?

Younger Drivers

Conformal	Non-Conformal
It brought the hazards to my attention quicker.	Yes, in the fog it helped to notice other cars.
In the fog one is able to notice the cars in front with the VES.	It did in the fog. Though sometimes it was more distracting than helpful. More important to ignore VES and concentrate on environment.
Helped with seeing the other cars and traffic light.	In the fog I was more prepared to handle "surprises" of cars ahead of me or the pedestrian.
I could see parked/stopped cars better. Allowed one to plan an avoidance response.	Helped Identify where cars were in the fog.
Helped me notice I was getting closer to a car.	Didn't help with a car that stops in front of you or pedestrians. Stoplight was also confusing.
Traffic light, oncoming traffic, same lane traffic position – especially in the fog.	The stoplight would appear in the bar – it was helpful.
Helped in low visibility fog and with the traffic lights.	Made me more aware of possible hazards, though there was no relation to a car getting closer. The search was intensive.
Helped with a approaching the stoplight and helped with stopped or slow cars.	Helped me notice cars and stoplights, but not the pedestrians.
Easier to see stopped or slow moving vehicles.	It allowed me to judge my speed.
It helped indicate traffic lights.	
I noticed the stoplight and was better able to calculate distance of car in front.	
In foggy conditions when there was a vehicle in front of me.	

Older Drivers

Conformal	Non-Conformal
It helped you anticipate traffic situations and reduce required reaction time.	It did not promise to announce hazards, only other cars.
I didn't have the impression that it did.	Distracted attention from roadway.
Traffic lights – parked cars in fog.	Helped on be more alert.
Once acclimated to look for them in non-fog trials, driver sought them out in fog, expecting them to indicate vehicle or traffic light.	Underlined the fact that a hazard was there, however if they were too commonplace they may loose effectiveness.
Judge distance better.	Made me aware that something was coming up.
They defined the limits of other vehicles – you don't need to know the size and shape of vehicle beyond the enhancement.	To some degree. They helped when figure came out into the road, but was too late to make much difference.
In the fog.	Could see other cars better.
Indicated while at the intersection.	An "awareness" of all vehicles in the area was increased to the point of distraction.
Clearly established presence of other vehicles.	
Parked cars especially.	

2. Did the enhancement of vehicles interfere with your ability to respond to hazards?

Younger Drivers

Conformal	Non-Conformal
Cars that were parked were also enhanced. It took a lot of attention to be aware of all things.	When pedestrian was crossing the bar seemed to be over area where I could have seen it.
Focused attention on pre-selected hazards, unforeseen ones are thus easy to miss.	During the day I focused on VES rather than surroundings.
Watching blue bars only made the pedestrian less expected than without bars.	Would rather know if the car/hazard was in my lane or not but more important if the hazard was moving.
Stopped in green light intersection based on the blue bar visual cue, even with no car apparent by the time I came to a complete stop.	Made me more anxious, didn't know if growing bars were in front or in other lane.
Focused on enhancements and missed the pedestrian walking in the road.	In clear conditions it was distracting – took away from my focus on the road/cars.
	Sometimes in the fog I wouldn't notice the traffic light enhancement – too worried about car in front.

Older Drivers

Conformal	Non-Conformal
Attending to enhancement, I did not detect the hazard as soon.	The VES seemed to be in the way of the first pedestrian.
Might have seen the pedestrian if I wasn't watching the blue bars.	No differentiation between parked and moving cars. In crowded situations the enhancement was distracting – it was on too much of the time.
Concentrating on the blue things, you're not as alert to other hazards.	A bit distracting. An intersection light appeared suddenly.
Found myself responding to color rather than outlines.	Enhancement bar actually blocked the roadway at its largest point (merely to point out a car to the side of the road or passing).
	I watched the blue bar instead of the roadway.
	Sometimes I was distracted by the enhancement.
	Tried hard to ignore blue bar and focus on the roadway.

3. What did you like about the Vision Enhancement System?

Younger Drivers

Conformal	Non-Conformal
Overall ability to drive safely enhanced.	Usefulness in the fog.
Draws attention to important information.	Told me traffic lights were approaching.
Helped keep track of other objects.	Very conspicuous blue bar.
Highlighted traffic light.	Accurate gauge of oncoming vehicles.
See better overall.	Heightened awareness.
Ease of knowing where other vehicles are.	Helped see hazards that were approaching.
Could see things much farther away.	Allowed me to anticipate moves I could make due to traffic situation.
Easier to see hazards in fog.	Made me more confident driving during day.
Helped me see stopped cars.	Possible to use it to prevent accidents.
Could see blue bars before I saw the cars.	Able to judge hazards better.
Better able to judge closeness/speed of other vehicles.	Helped me remember things were coming up.
Gave broad information about the driving environment.	Helped me remember vehicles were approaching.

Older Drivers

Conformal	Non-Conformal
Good for vehicles coming towards you.	Visibility.
Good for vehicles parked in travel direction.	Consistency.
Increased awareness of driving environment.	Color of it.
Clear visibility in the fog.	Alerts to danger.
Concentrate on one color.	Accurate and consistent.
Felt safer using the display.	Helped identify possible hazards.
Helped see objects some distance ahead.	Showed up close to hazards.
Did not block vision.	Showed hazards when the visibility was bad.
Prompted attention to possible obstacles.	Early warning.
Recognized boundaries of other vehicles.	Drove faster than usual when using display.
Called attention to traffic lights.	Showed where vehicles were.
	Determine distance from hazard.

4. What did you dislike about the Vision Enhancement System?

Younger Drivers

Conformal	Non-Conformal
Could fatigue on long drives.	Made me panicky and had potential to over react.
Tunneled attention.	Did not enhance abilities in the daytime.
Conformal images should not be seen through other vehicles.	Position on screen - should be in the corner.
Distracting when too many vehicles present.	Did not show cars in my lane.
Not easy to tell other vehicles distance when bar is the only indicator.	Did not show pedestrians.
Was only installed on bumpers of cars - makes you only look for cars.	Stoplight symbol was confusing.
Drew attention away from pedestrians and other hazards.	Bar stayed in one spot - should position itself where vehicles were.
Distracting during normal daytime driving.	With many cars in environment it became confusing.
Shape seemed unrealistic.	Distracting - trying to match bars to cars.
Location of bar did not seem realistic.	Covered up portion of view.
Could not tell if vehicles were on my side of the roadway.	Changing size of bar made me dizzy.
Distracting from other things in driving environment.	Only one bar for all situations.

Older Drivers

Conformal	Non-Conformal
Distraction, too many blue bars.	Inconsistent for traffic lights.
No way of enhancing pedestrian.	Light intensity could be lowered.
Did not know what to make of enhanced traffic lights.	Took away attention from other hazards.
Expanding size did not seem right.	Did not identify position of other vehicles.
Encouraged me to drive when I should not.	Did not give speed of vehicle I was following.
Distracted from other hazards in environment.	Distraction on busy highway.
Discouraged attention through over reliance.	Did not show where approaching car was.
Distraction from parked cars.	Obstructed driving view.
Did not feel in control.	Confusion with other extraneous stimuli.
Felt visually uncomfortable.	Added another factor for drivers attention.
Unsure of what hazards would be revealed.	Treated all vehicles with the same response.
	Size of blue bar.

5. In what traffic situations would VES benefit?

Younger Drivers

Conformal	Non-Conformal
Snow and rain.	Any low visibility conditions.
Bright sunlight.	Rain.
Night driving.	Pedestrians.
Rainy nights.	Snow.
Burned out and covered up tail lights of other vehicles.	Fog.
Smoke, haze and smog.	Stoplights.
Blizzards.	Railway crossings.
Rural driving.	Animals crossing the road.
	Passing vehicles.
	Turning on a green light.
	Hail.

Older Drivers

Conformal	Non-Conformal
Monotonous country driving.	Night Driving outside of the city.
Blind approaches.	Car entering the intersection.
Parked vehicles that were starting up.	In rainy weather.
Vehicles crossing at right angles.	Seeing people.
Night vision.	
Congested areas.	
Pedestrians.	
Bicycles.	
Very bright sunlight.	

6. In what traffic situations would VES detract?

Younger Drivers

Conformal	Non-Conformal
Cluttered environments/many people.	Normal driving conditions.
During rush hour.	Winter conditions.
Clear daylight conditions.	Busy traffic on a clear day.
Over-reliance on the system.	Very crowded highways and streets.
	Where many parked cars are present.
	Busy intersection with many cars.
	Daytime driving.
	Difficult to see children.
	Not needed when conditions are optimal.

Older Drivers

Conformal	Non-Conformal
Congested city.	Depends on frequency of false alarms.
Busy freeway.	Detracted from attention to the roadway.
With many parked vehicles.	Icy conditions. May cause improper reactions.
Tendency to depend on it too much.	Extremely heavy traffic.
Pedestrian crossings.	City streets where cars are parked on both sides of the roadway.
Under normal driving conditions.	