

**Display of HUD Warnings to Drivers:  
Determining an Optimal Location**

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**Herbert Yoo, Omer Tsimhoni,  
Hiroshi Watanabe, Paul Green,  
and Raina Shah**

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16. Abstract <p>To design automotive head up displays, the extent to which HUDs interfere with detection of elements of the road scene (other vehicles, edge markings, signs, etc.) as a function of HUD location needs to be determined. In this experiment, 24 subjects sat in a driving simulator and watched a videotape of a real road. To encourage them to scan the road as they would while actively driving, subjects pressed a key whenever they detected predetermined events in the road scene (passing cars, tail lights of a leading vehicle, road signs on the right edge of the road). In addition, subjects pressed a key when an amber-colored warning triangle appeared on the HUD at one of 15 locations.</p> <p>Response times to HUD warnings, and to a lesser extent, detection probability, varied with warning location. The mean response times ranged from 842 ms to 1390 ms. The fastest response time was obtained at 5 degrees to the right of the center. The detection probability for most locations (12 of 15) was 0.97 or higher. The HUD task did not significantly interfere with road event detection. Response times to car signals increased from 1175 ms to 1260 ms when the HUD task was added, and the detection probability did not change when the HUD task was added. The corner locations were perceived by many subjects to be worse than central locations, and they disliked the center location and the lower center. If one location were to be chosen, it would be located 5 degrees right or left of the center.</p>					
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# Display of HUD Warnings to Drivers: Determining an Optimal Location

UMTRI Technical Report 99-9

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## 1 ISSUES

1. Does location affect response time and detection probability of HUD warnings?
2. Does the presence of a HUD (1) interfere with detection of and (2) alter response time to events on the road?
3. What are the best and worst locations for a HUD as reported by the subjects?

## 2 TEST PLAN

Subjects	Young (20-29)	Old (65-78)
Male	6	6
Female	6	6

**Conditions:** testing of road events and HUD warnings

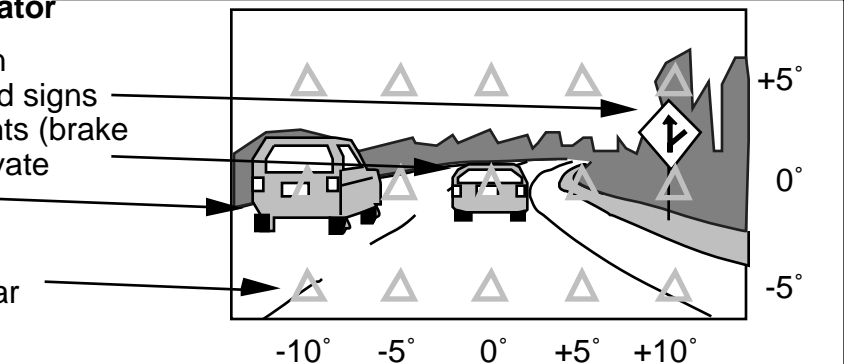
1. Pre-test road baseline (only road events tested)
2. Pre-test HUD baseline (only HUD warning tested)
3. Main experiment (road and HUD tested simultaneously)
4. Post-test baselines (same as pre-tests)

### Driver Tasks in the Simulator

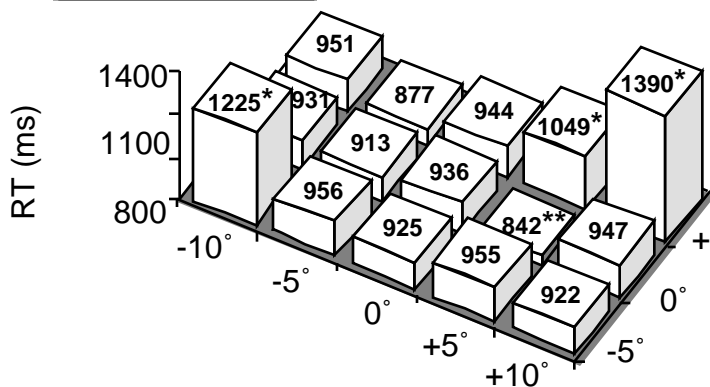
Press the "Road key" when

1. the lead car passes road signs
2. the lead car's signal lights (brake lights, turn signals) activate
3. cars pass the lead car

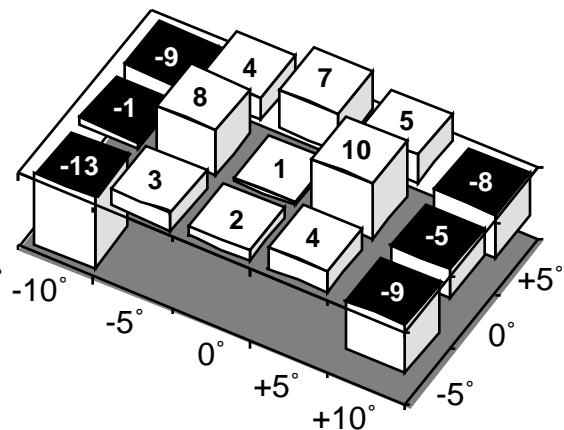
Press the "HUD key" when HUD warnings appear on the windshield



## 3 RESULTS

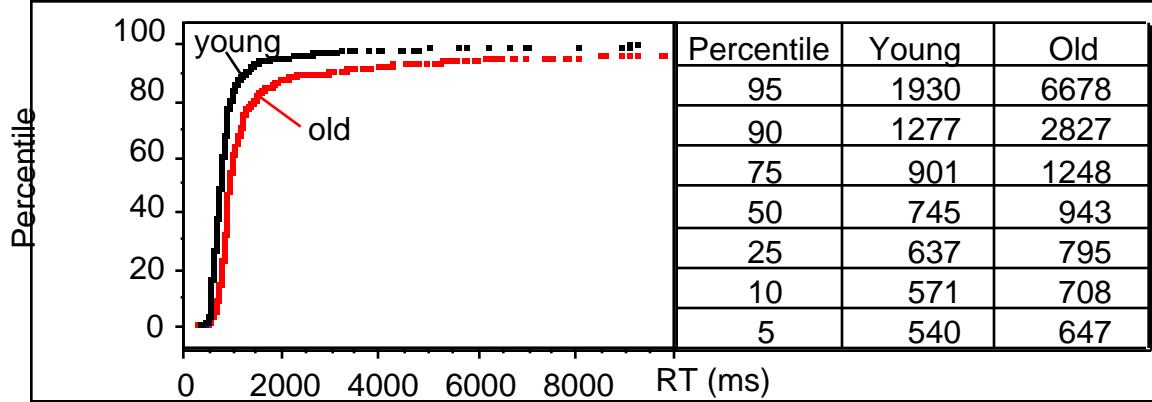


HUD response time for each location  
(\* = significantly different than all others,  
\*\* = significantly different than some)

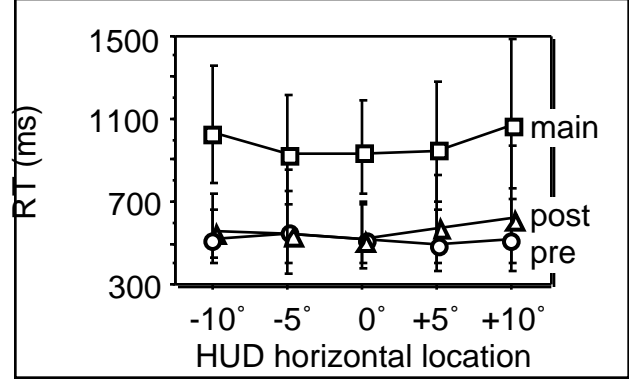


A sum of subject responses for "best" and "worst" locations for HUD

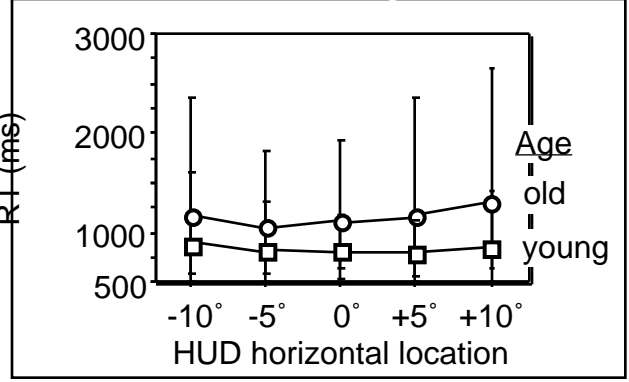
### HUD cumulative RT



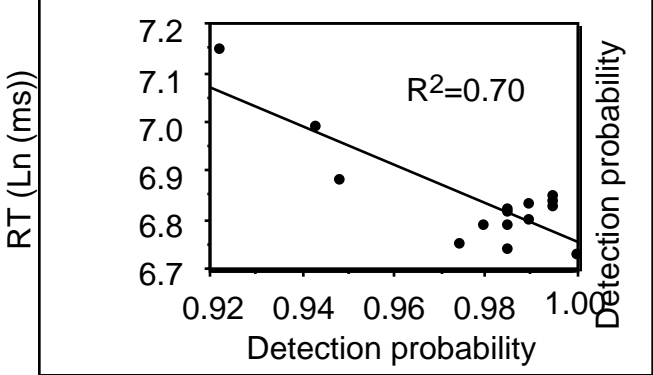
#### Effects of location & task: HUD RT



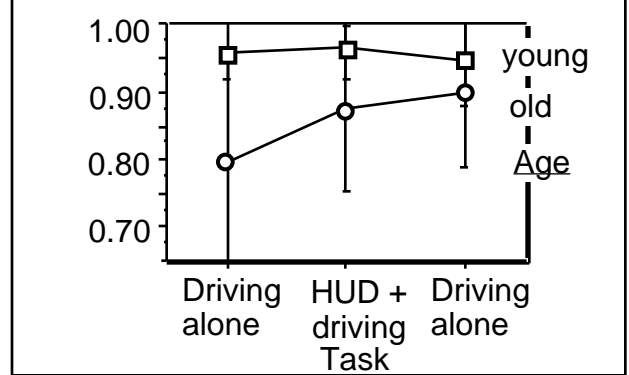
#### Effects of location & age: HUD RT



#### Correlation of RT & detection prob.: HUD



#### Effects of age & task: car signal detection



## 4 CONCLUSIONS

1. Response times and detection probability of center locations were generally consistent. The fastest response time was located 5 degrees to the right of center.
2. Some interference effects of the HUD were evident in this experiment. However, response times and detection probabilities to road events were not significantly worse when performed concurrently with the HUD detection task.
3. Subjects did not like locations that were farther than 5 degrees horizontally from the center. They preferred locations where overlap with road events was minimal.

## PREFACE

This research was funded by the University of Michigan Intelligent Transportation Systems (ITS) Research Center for Excellence, formerly the IVHS Research Center for Excellence. The program is a consortium of companies and government agencies, working with the University, whose goal is to advance ITS research and implementation.

The current sponsors are:

- Ann Arbor Transit Authority
- American Automobile Manufacturing Association (AAMA)
- Michigan Department of Transportation
- Nissan Motor Company
- Road Commission of Oakland County
- Ryder Integrated Logistics
- Toyota Motor Corporation
- United States Department of Transportation

We would like to thank the lead corporate sponsor for this project, Nissan Motor Company, for their support.



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## INTRODUCTION

Head-up displays (HUDs) have been used in motor vehicles to show speed, vehicle malfunction warnings, radio settings, and other information. For these purposes, using a HUD instead of an instrument panel display maintains the direction of gaze toward the road, enhancing driving safety. When drivers look at the speedometer on the instrument panel, they may not see a critical event which needs immediate attention, such as a vehicle in their path. With a HUD, only a change in accommodation is needed, not more time consuming eye and head movements. For situations where an immediate response is required, such as a reacting to a collision avoidance warning, the reduction in response time from HUD display of the warning could be a significant safety benefit.

HUDs have been widely used in aircraft for decades, but until recently, they have been a novelty item for automotive applications. Based on the contributions that HUDs have made to aircraft safety, potential automotive safety benefits, and driver convenience, limited production of automotive HUDs has occurred (1988 Nissan Silvia, 1988 Oldsmobile). To support development, several studies have been conducted to assess the benefits of having HUDs in automobiles. These studies and other studies relevant to automobiles have examined (1) the general benefits of HUDs, (2) display location, (3) image distance, (4) size, (5) color, and (6) brightness and contrast. A tabular summary of this literature appears in Appendix A. Studies are grouped according to dependent measure type (performance vs. subjective) and context (aircraft, automotive).

The literature suggests that HUDs improve the driver's ability to access display information while viewing the forward scene and that the ideal location for a HUD is directly ahead of the driver, about 10 degrees below the forward line of vision. While the literature contains several studies in which multiple locations for HUD placement were examined, no studies have examined a sufficient number of locations to develop an empiric relationship between angle from the line of sight and some performance measure. Therefore, the basic question, where is the best location for a HUD warning, remained unanswered. This question was of particular interest to the project sponsor, Nissan. Traditionally, automotive HUDs have been displayed on the periphery of the visual field so as not to interfere with drivers' vision of the road and because immediate responses were not needed. However, for a critical warning signal positioned in the periphery, drivers may not respond fast enough, or may even miss the warning signal, increasing crash risk.

Since the literature did not provide the definitive answer desired, the experimental portion of this study was conducted. This experiment examined three questions:

## **Introduction**

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1. How does the location of an automotive HUD affect the detection probability and response time to HUD warnings while driving?
2. Does the presence of a HUD decrease the detection probability of road events and response time to them?
3. What are the best and worst locations for a HUD as reported by the subjects?

## TEST PLAN

### Overview

In this experiment, subjects viewed videotapes of road scenes recorded from a driver's perspective and shown on a projection screen. At the same time, the subjects responded to events occurring in the road scene as well as HUD warnings appearing on the windshield. Subjects pressed one of two buttons: one for the HUD and one for the events in the scene. There were 15 different locations on the windshield where the HUD warning could appear and 3 different types of events in the road scene. Dependent variables were the response times and number of errors for each type of event.

### Test participants

Twenty-four licensed drivers participated in this experiment, 12 younger (20-29 years old, mean of 23) and 12 older (65-78 years old, mean of 71). Within each age bracket there were 6 men and 6 women. Participants were recruited via an advertisement in the local newspaper, from the UMTRI subject database, and from among friends of the experimenters. All were paid \$35 for their participation.

Subjects were tested for visual acuity, depth perception, peripheral vision, and color vision. The younger subjects had corrected visual acuity ranging from 20/35 to 20/13. The older subjects had corrected visual acuity ranging from 20/40 to 20/17. Most subjects had a stereo depth perception of at least 70 s of arc in angle of stereopsis. All but one had a peripheral vision range of 70 degrees at the minimum. All subjects had normal color vision.

Subjects reported driving from 4,800 to 48,300 km (3,000 to 30,000 miles) per year with a mean of 18,400 km (11,400 miles) per year. Of the 24 subjects, 19 reported no crashes with the last 5 years, 4 reported 1 crash, and 1 reported 2 crashes. Four subjects had, at least once before, driven an automobile with a HUD. One subject had experience with an aircraft HUD.

### Development of the HUD

Since the focus of this experiment was to determine the effect of location of HUDs on visual performance, a wide range of locations where information presented by a HUD could appear was examined. Figure 1 shows the 15 location matrix examined (5 columns by 3 rows). The columns were 5.0 cm (2 in.) apart and the rows 9.7 cm (3.8 in.). Figure 2 shows all possible test images superimposed on the road scene as seen by the subjects. Normally, only one triangle appeared at a time. Notice that the centermost triangle overlaps the lead vehicle.

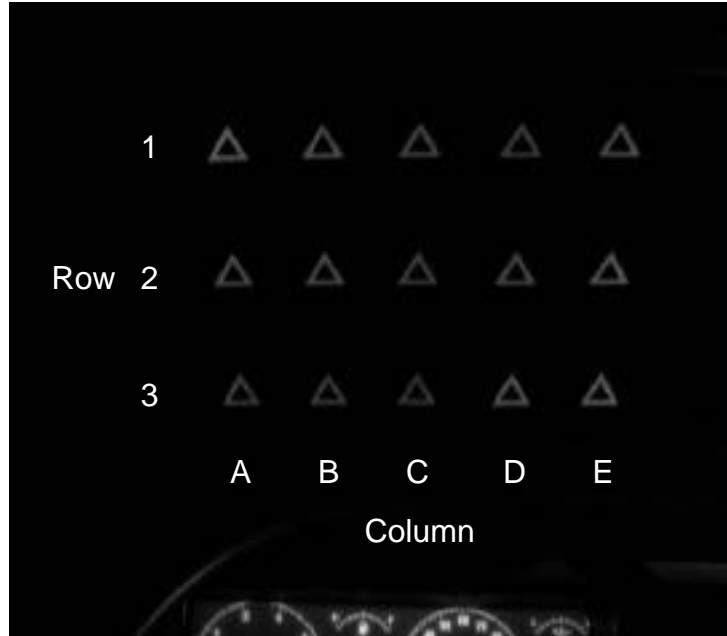


Figure 1. All 15 locations of the HUD activated without the road scene.



Figure 2. All 15 locations of the HUD activated with the road scene. The color of the triangles was changed to white in this figure for clarity.

All the subjects were seated in the vehicle mockup so that their eye positions were fixed at a common height, using seat adjustments and pillows. This was done by having the subjects look through a tube with their right eye and align the centermost triangle of the HUD with a circle on the screen ahead. The circle was placed at a fixed position

## Test plan

relative to the screen (where the lead car would be). This ensured that all subjects' line of sight was directly on the lead car and that the centermost triangle overlapped the lead car.

From the fixed eye position, the centermost triangle was even with the line of sight of the subject, both vertically and horizontally. As shown in Figure 3a and 3b, the triangles were spaced approximately 5 degrees apart.

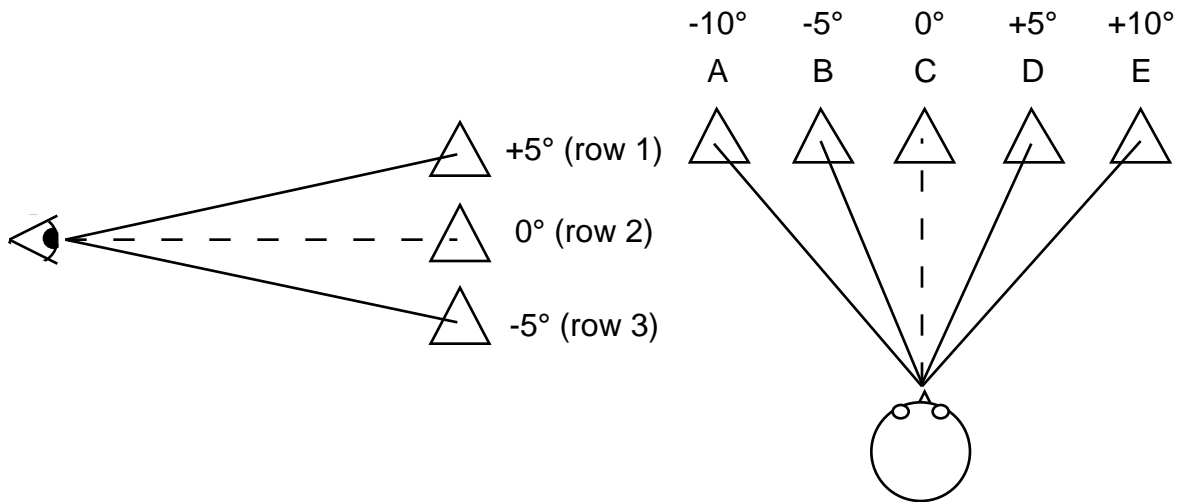


Figure 3a. Vertical position of rows

Figure 3b. Horizontal position of columns

Figure 4 provides the warning signal details. The specifications of the triangles were provided by the sponsor of the study.

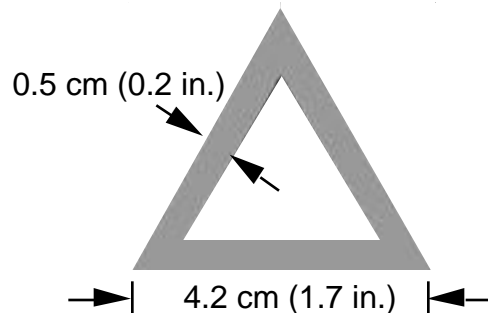


Figure 4. Amber-colored equilateral triangle as oriented on the HUD

The focal distance of the triangles ranged between 94 and 106 cm (37 in. and 42 in.), the sponsor-specified range of existing HUDs. The contrast ratios, independently measured for each occurrence, ranged from 1.3 to 6.5, where contrast was defined as:

$$\text{contrast} = (\text{combined target and background luminance}) / \text{background luminance}$$

## Test plan

---

The contrast data for each location are shown in Table 1. For an alternative definition of contrast ( $[\text{target luminance} - \text{background luminance}]/\text{background luminance}$ ), subtract 1 from the given values.

Table 1. Average contrast (and standard deviation) for each location

	A	B	C	D	E
1	1.5 (0.1)	1.4 (0.0)	1.3 (0.0)	1.9 (0.5)	2.6 (1.7)
2	1.9 (0.4)	1.5 (0.2)	3.0 (1.1)	2.9 (2.2)	3.1 (1.1)
3	1.8 (0.5)	1.7 (0.2)	1.8 (0.4)	1.4 (0.0)	3.0 (1.0)

The typical luminance and contrast levels for some objects in the road scene are shown in Table 2. The average luminance of the HUD triangle was 1.62 cd/m<sup>2</sup>.

Table 2. Typical luminance of objects on road and their contrast with HUD triangles

Object	Luminance (cd/m <sup>2</sup> )	Contrast with HUD triangle
Lead vehicle	0.44	4.68 : 1
Passing vehicle	0.45	4.60 : 1
Sky	4.40	1.37 : 1
Road	3.57	1.45 : 1
Landscaping	2.00	2.23 : 1

Subjects were shown 120 triangles over 4 runs. Each triangle was presented for up to 10 s after which the triangle was removed and the response was considered a miss. Otherwise, the triangle was removed as soon as the subject pressed a button within the 10 s response period.

### Development of road events

To more realistically draw attention to the road and not the HUD, the road scene contained three types of events to which subjects responded: (1) passing vehicles, (2) taillights of the lead car, and (3) road signs. The location of the three types of events spanned the screen from left to right, respectively, leading to scan patterns believed to resemble real driving. Also, to ensure other vehicles would pass, the research vehicles in the videotapes were driven 8 km/h (5 mph) below the limit.

The passing vehicles event required the subjects to respond when the rear bumper of a vehicle passing on the left side of the lead car was aligned with the rear bumper of the lead car (Figure 5). The taillights event required the subjects to respond when the brake lights or either of the turn signal lights of the lead car were activated (Figure 6). The road signs event required the subjects to respond when a yellow, diamond-shaped road sign on the right side of the road was aligned with the lead car's rear bumper (Figure 5). The subjects were asked to respond to all road events with one button. The

## Test plan

subjects were given a response window of approximately 5 s for the passing car event and the road sign. For the lead vehicle taillight events, the subjects were given the length of the taillight activity plus 1 s to respond.



Figure 5. A passing vehicle aligned with the lead car and a yellow diamond-shaped road sign aligned with the lead car.



Figure 6. Lead car with the left turn signal activated, brake lights activated, and the right turn signal activated (left to right, respectively)

Four road scenarios were presented to the subjects. The HUD warnings to which drivers had to respond were randomly distributed across the road with an interval time of  $25 \pm 1.5$  s. The road events could not be perfectly controlled due to small differences in congestion and a different number of road signs. However, the mean time between two events was similar for all four roads ( $6.5 \pm 4.5$  s). Table 3 shows the quartile values of time between events in each of the roads. The lower quartile value in Road 1 was under 2.5 s, which would require the driver to respond almost simultaneously to two or more events. The upper quartile value in Road 1 was over 9.4 s, which would allow the driver some rest between responses.

Table 3. Time between events (quartile values)

	Actual road	No. of events	Duration of road (min)	25th percentile (s)	Median (s)	75th percentile (s)
Road 1	US-23 N	124	13	2.475	5.800	9.425
Road 2	US-23 S	126	13	2.480	5.750	9.230
Road 3	US-23 N	139	15	3.050	5.880	9.360
Road 4	US-23 S	134	14	2.575	6.220	8.800



### Test materials and equipment

The road scene was recorded on US-23, a 105 km/h (65 mph) divided expressway, between M-14 and I-96 near Ann Arbor, Michigan. Both northbound and southbound routes were recorded between 1:30 PM and 3:00 PM in May 1998. The road scene was recorded with a small camera just behind the rear view mirror in a 1991 Honda Accord wagon. A microphone was placed under the hood of the car to collect engine, traffic, and road noise.

The lead vehicle in the road scene was a 1991 Ford Taurus which activated its brake lights, left, and right turn signal lights in random order and at random time intervals. The time of taillight activation directed by speech output to the driver from a custom program running on a laptop computer inside the lead car. The brake lights were lit for approximately 3 s at a time. The turn signals were activated for 4 blinks, (approximately 3 s).

The HUD was simulated with an acrylic sheet acting as a reflective surface. As Figure 7 shows, the subjects could see the road scene through the sheet. The sheet also allowed for the subjects to see a reflection of the HUD images that originated from two flat-panel LCD monitors lying horizontally on the dashboard (Figure 8). The videotapes of the road scene were played on a VCR and projected onto a large screen in front of the subject.

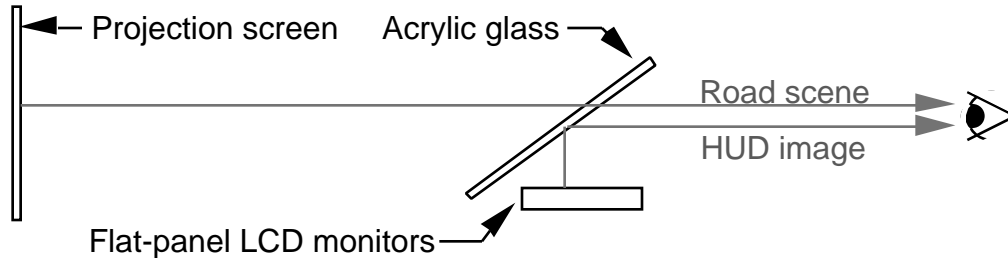


Figure 7. Simulated HUD



Figure 8. Windshield and LCD monitors

Psyscope software (version 1.2.1 PPC, Carnegie Mellon University), running on a Power Macintosh 9500/150, was used to display HUD warnings and to collect subject responses. Subjects responded by pressing a two-button keypad: one button for the head-up display, one for all events in the road scene.

A lipstick-sized camera recorded the subjects' fingers and another overhead recorded the flat-panel LCD monitors on top of the instrument panel that displayed the HUD warnings. A low-light camera recorded the subject's face. The three video signals from the cameras and the road scene from the VCR were merged into a split-quad image (Figure 9).

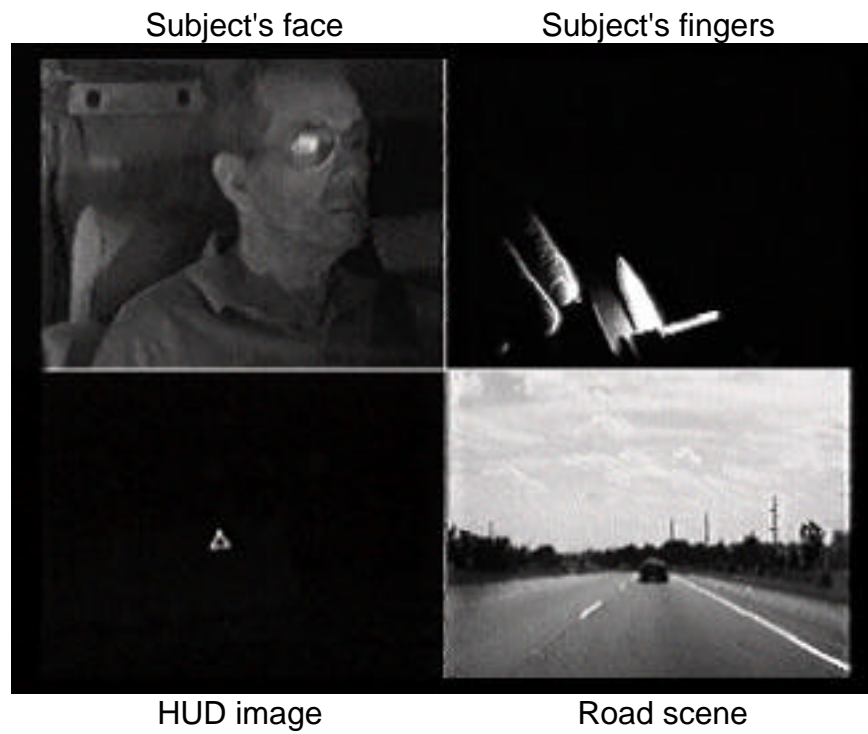
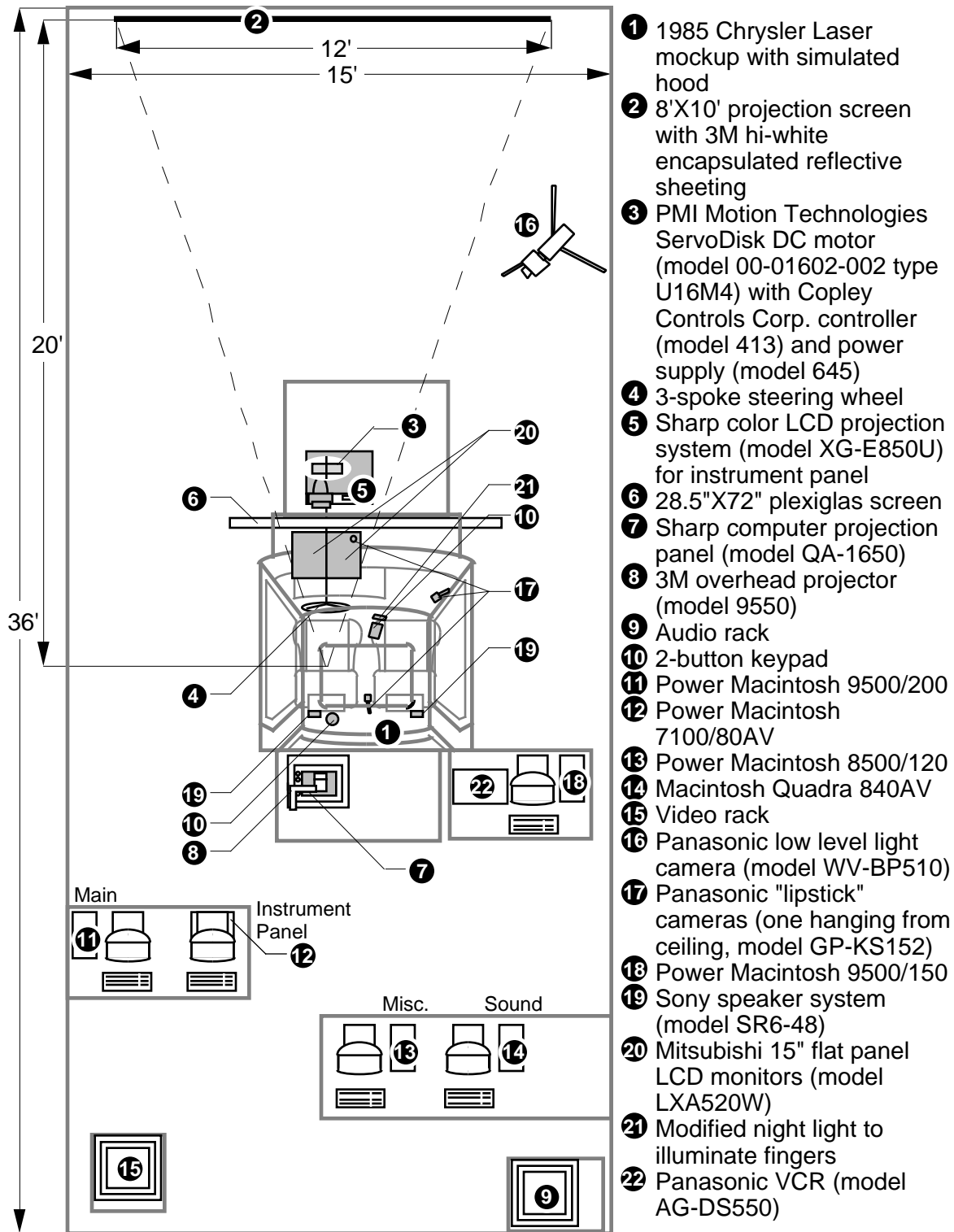


Figure 9. Quad-split image

A Titmus model OV-7M Vision Tester was used to check the vision of subjects. A Minolta LS-100 photometer was used to measure luminance values. The overall arrangement of equipment at the time the experiment was conducted is shown in Figure 10.

**Test plan**



- 1 1985 Chrysler Laser mockup with simulated hood
- 2 8'X10' projection screen with 3M hi-white encapsulated reflective sheeting
- 3 PMI Motion Technologies ServoDisk DC motor (model 00-01602-002 type U16M4) with Copley Controls Corp. controller (model 413) and power supply (model 645)
- 4 3-spoke steering wheel
- 5 Sharp color LCD projection system (model XG-E850U) for instrument panel
- 6 28.5"X72" plexiglas screen
- 7 Sharp computer projection panel (model QA-1650)
- 8 3M overhead projector (model 9550)
- 9 Audio rack
- 10 2-button keypad
- 11 Power Macintosh 9500/200
- 12 Power Macintosh 7100/80AV
- 13 Power Macintosh 8500/120
- 14 Macintosh Quadra 840AV
- 15 Video rack
- 16 Panasonic low level light camera (model WV-BP510)
- 17 Panasonic "lipstick" cameras (one hanging from ceiling, model GP-KS152)
- 18 Power Macintosh 9500/150
- 19 Sony speaker system (model SR6-48)
- 20 Mitsubishi 15" flat panel LCD monitors (model LXA520W)
- 21 Modified night light to illuminate fingers
- 22 Panasonic VCR (model AG-DS550)

Figure 10. Plan view of UMTRI's driver interface research simulator

**Test activities and their sequence**

Each subject began by completing consent (see Appendix B) and biographical forms (see Appendix C), and by having their vision checked. (The entire experiment protocol is in Appendix D.) The subject was then seated in the driving simulator and the subject's seating position was adjusted (adding a seat cushion when necessary) to reach the specified eye position. The subject then practiced responding to road events. After the training session, pre-test road events baseline data and HUD baseline data were collected.

For baseline data for the road events, subjects responded only to road events of an 8 min segment of Road 2. For baseline data for the HUD, subjects responded to triangles (6 to 14 s apart) while a still picture of a road was on the screen.

Four runs of the task were completed by each subject. The order was randomized for each of the six subjects within the age and gender groups. The subject was responded both to road events and to the HUD (triangles appearing at an interval of 21 to 29 s). The subject was given a mandatory 5 min break after two runs.

After the four runs, the post-test road events baseline and HUD baseline data were taken. Then the subject filled out a questionnaire (see Appendix E) and was paid. In the questionnaire, the subjects were asked to evaluate the HUD and tasks used in the experiment. The subjects were also asked to identify the three best and three worst locations for a HUD on a 3 row by 5 column grid.

Table 4. Summary of activities and their sequence

Activity	Time (min)	HUD	Road scene
Pre-experiment forms and setup	~10	n/a	n/a
Training	~10	n/a	n/a
Pre-experiment road baseline	8	No	Yes
Pre-experiment HUD baseline	5	Yes	Still picture
Run 1	13-16	Yes	Yes
Run 2	13-16	Yes	Yes
Break	5	n/a	n/a
Run 3	13-16	Yes	Yes
Run 4	13-16	Yes	Yes
Post-experiment road baseline	8	No	Yes
Post-experiment HUD baseline	5	Yes	Still picture
Post-experiment forms	~10	n/a	n/a

### Data collection

The same computer program that controlled the HUD display collected the response times. Each videotape had a matching file that consisted of response windows (onset and duration) for events on the road and for HUD warnings. After the videotape and the computer program were simultaneously started, a response window would open synchronous to each HUD warning and road event appearing on the videotape. HUD windows opened when the HUD warning appeared on the display and closed after the subject responded. If the subject did not respond to the HUD warning within 10 s of its appearance, the HUD warning was cleared from the display and the window was closed. Windows for car signal lights appeared 250 ms before the first appearance of the light on the videotape and lasted for 4 s. Windows for other road events appeared 2 s before the approximate onset of the event (e.g., before a passing vehicle was aligned with the lead vehicle) and lasted for 6 s.

When subjects pressed on the HUD response key, their response was saved in a data file. Based on the presence of a HUD event window at the time the key was pressed, one of the two labels was attached to the data file: (1) "hit" - the key was pressed when a HUD event window was open or (2) "false alarm" - the key was pressed when no HUD event window was open. When no key was pressed within 10 s from warning appearance, "missed signal" was attached to the data file. When subjects pressed on the car and road event key, their response was recorded in the data file following the same logic. However, since only one key was used for recording two types of events, the following criteria were used: (1) if only one window was open and the key was pressed, the key press was registered to that window, (2) if no window was open and the key was pressed, a false alarm was registered to a road event, and (3) if two windows were concurrently open, the car-event window took precedence over the road-event window.

Eight data files were collected for each subject. The data files included: all key presses made in that run, the response label (e.g., hit, false alarm), window onset time, key press time, and other descriptive data. Approximately 19,000 data points were obtained for all runs of all subjects.

Response time was then calculated for all the relevant events by subtracting the time of event onset from time the key was pressed. Some descriptive information was added to the HUD responses (e.g., contrast level, HUD position). All time values were then log transformed (see detailed explanation in the results section). In order for an ANOVA to be performed, 64 missing HUD responses were filled with a conservative value of 9.21, which is the natural log transform of 10000 ms.

**Test plan**

ANOVA was used to identify significant differences in the experiment (Table 5). Age and gender were always between subject factors. Within subject factors varied according to the signal (e.g., horizontal and vertical only in HUD warnings). In addition to the main ANOVA that was performed for each signal/measure combination, additional analyses were performed for confounded factors. For example, road effect replaced run effect in the model since the two were confounded.

Table 5. Summary of ANOVA computations

Note: Bold rows indicate main analyses for each signal/measure combination.

Signal	Dependent measure	Table name	Between subject		Within subject						
			Age	Gender	Horizontal	Vertical	Run	Road	Trial order	Baseline order	Contrast level
HUD	Response time	<b>Main ANOVA</b>	✓	✓	✓	✓	✓		✓		
		Road effect	✓	✓	✓	✓		✓	✓		
		Baseline order	✓	✓	✓					✓	
		Contrast level	✓	✓	✓						✓
	Detection probability	<b>Main ANOVA</b>	✓	✓	✓	✓	✓		✓		
		Road effect	✓	✓	✓	✓		✓	✓		
Baseline order		✓	✓	✓					✓		
Car signal lights	Response time	<b>Main ANOVA</b>	✓	✓			✓				
		Road effect	✓	✓				✓			
		Baseline order	✓	✓						✓	
	Detection probability	<b>Main ANOVA</b>	✓	✓			✓				
		Baseline order	✓	✓						✓	
Road events	Detection probability	<b>Main ANOVA</b>	✓	✓			✓				
		Baseline order	✓	✓						✓	

## RESULTS

### General introduction

Throughout the experiment, each driver responded to 150 HUD warnings and approximately 640 events on the road. Altogether, the database that was used for the statistical analysis consisted of approximately 19,000 data points.

The first part of the results section discusses responses to HUD warnings while driving a car. Significant factors that affected drivers' response times and detection probabilities are shown. The second part shows learning and fatigue effects and discusses HUD warning detection with and without driving. A short discussion of luminance contrast is then shown in part three. The next two parts deal with responding to events on the road. Response time and detection probability for car signal lights are shown in part four, and detection probability for the other road events are shown in part five. Finally, subjective preferences of locations are shown in part six.

### Data transformation

Since response times are usually lognormally distributed, HUD response times were transformed using a natural log ( $\ln$ ) to provide normality prior to analysis, a requirement of the ANOVA procedure utilized. Figure 11 shows the before and after distributions. The floor effect, which caused the original distribution to be asymmetric, was almost completely cancelled by the transformation, although a slight asymmetry between the right and left tails exists. Note that the transformed data is distributed more evenly, and therefore its peak is not as high as in the original data.

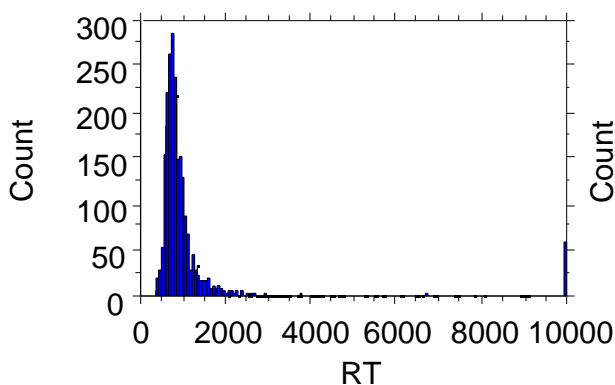


Figure 11a. HUD RT distribution with original data

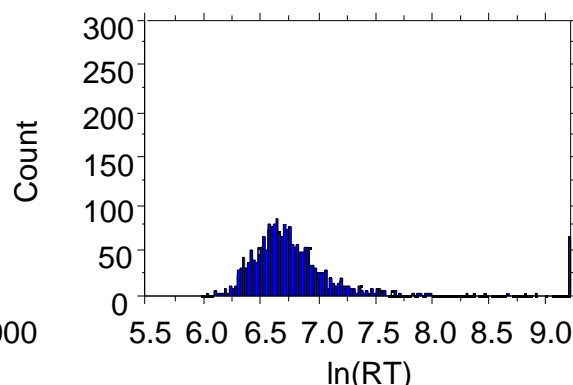


Figure 11b. HUD RT distribution after logarithmic transformation

Although the ANOVA utilized the transformed data, data transformed back from that analysis (inverse transform) are shown in the tables and figures to aid interpretation by the reader. Therefore, standard deviations are skewed so that the lower standard



## Results

deviation is narrower than the higher standard deviation. This makes sense since the original data are distributed more densely below the median than above it.

The repeated measures ANOVA of transformed response time included age and gender as between subject factors and run, trial, row, and column as within subject factors (see Table 21 in Appendix G).

### Responses to HUD warnings while driving a car

#### Cumulative distribution

Figure 12 presents the cumulative distribution of response time to HUD warnings. Ninety five percent of older drivers' responses were under 6678 ms, while 95 percent of younger drivers' responses were under 1930 ms. Additional percentile values are shown in the figure.

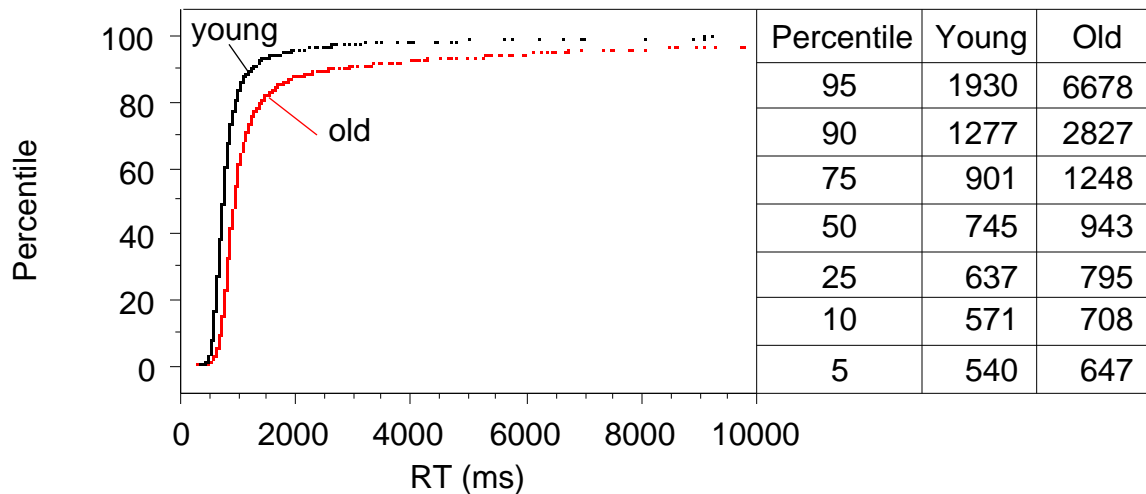


Figure 12. Cumulative distribution and tabular summary of HUD response times

#### Effect of HUD warning location

How does latency and probability of detecting a HUD warning vary with location? For the matrix of 15 locations (3 rows by 5 columns), horizontal location was highly significant ( $p=0.0001$ ), vertical location was marginally significant ( $p=0.055$ ), and the interaction between horizontal and vertical locations was highly significant ( $p=0.0001$ ).

Each cube in Figure 13 represents the mean across 24 subjects of the mean response time (ms) in the transformed form for each of the 15 HUD warning locations. A Fisher's post hoc test for the different columns showed a significant difference between column A (1028 ms) and columns B, C, D (915, 935, 945 respectively), between column E (1066 ms) and the middle columns, but not between A and E or between the middle columns. The middle row (913 ms) was different from the top (1028 ms) and the bottom row (990 ms), but the top and bottom rows were not significantly different from each

## Results

other. A post hoc test for the specific locations showed a significant pair-wise difference between E1, A3, D1, and each of the other locations ( $p=0.0001$ ). D2 was significantly smaller than only some of the other locations.

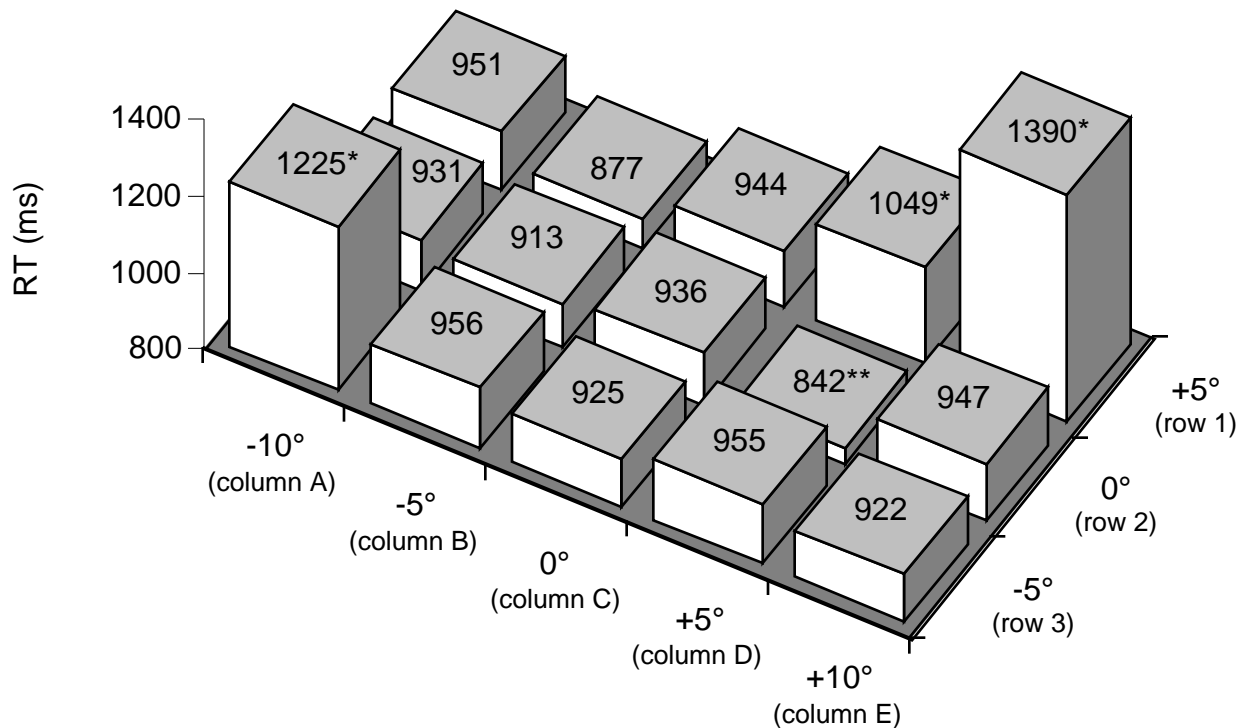


Figure 13. HUD response time for each location  
 (\*=significantly different than all others, \*\*=significantly different than some)

Overall, the mean response times for each location followed the eccentricity hypothesis — drivers responded more slowly to HUD warnings in farther locations from the center. This trend, however, is only true when comparing for column average or row average. Location E3, for example, was the fastest in its row although it was positioned 10 degrees to the right of the center. These departures could be due to contrast as a confounding effect. Warnings in E3 may have had a higher contrast than others in that row, thus making the response faster. However, detailed analysis of contrast (discussed later) did not confirm this premise.

The fastest response time of all tested locations was achieved 5 degrees to the right of the center at eye level (D2). Although not specifically tested in this experiment, it is probably due to a tradeoff between distance from the center and interference with overlapping events on the road.

Each solid in Figure 14 represents the mean detection probability across all subjects — the portion of HUD warnings that were not detected within 10 seconds. Each cube accounts for 192 detection opportunities. There was a negative correlation (-0.93) between response time and detection probability. Locations with long response times had lower detection probabilities. In A3, D1, and E1, the detection probability was

## Results

95 percent or lower. As in the analysis of response times, an eccentricity hypothesis did not completely explain the results.

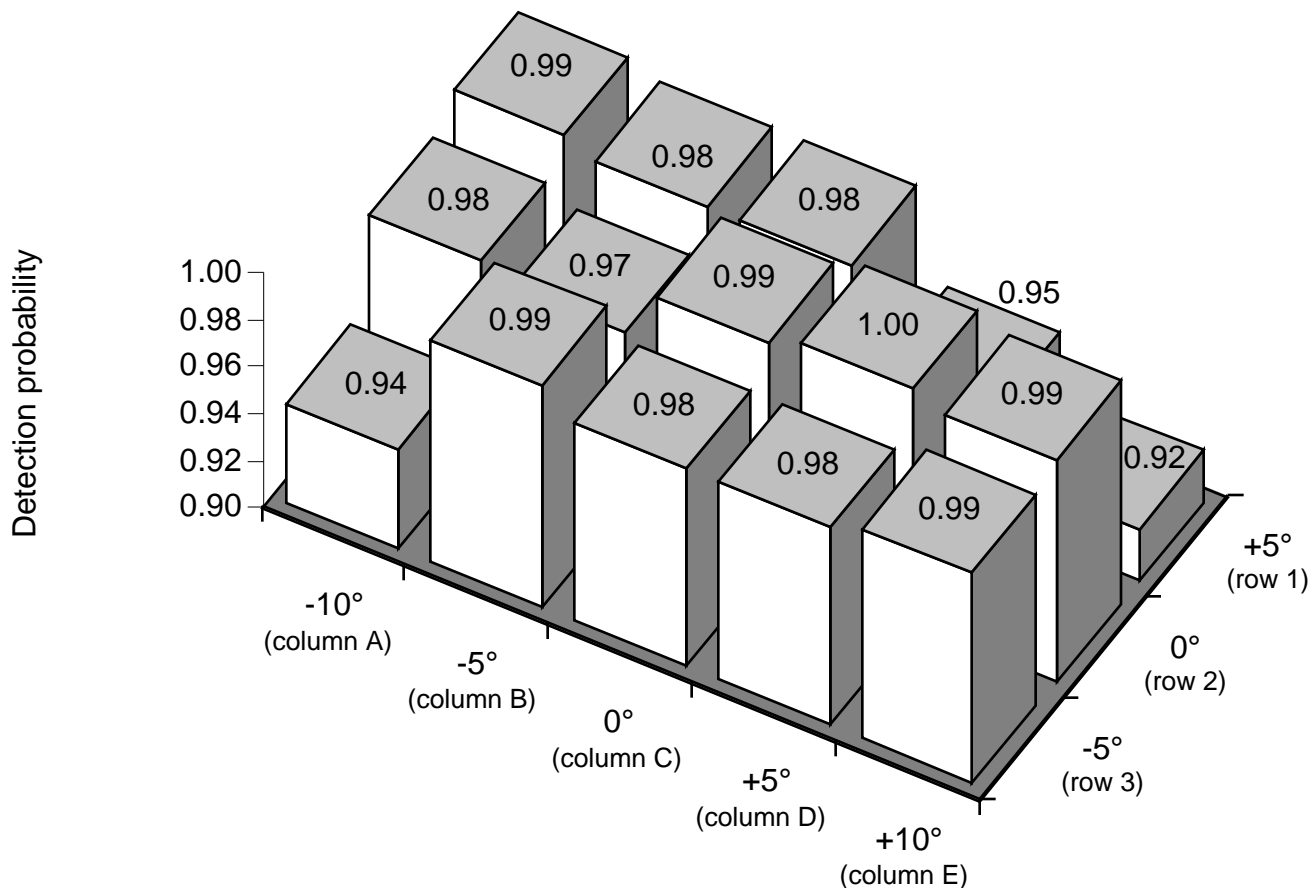


Figure 14. HUD detection probability for each location

### Effect of age

Older drivers responded to HUD warnings significantly slower than younger drivers ( $p=0.0008$ ). On average, response time to HUD warnings was 1153 ms for older drivers and 826 ms for younger drivers, a 40 percent difference.

The pattern of response time across different columns of the HUD warning was not similar for younger and older drivers (Figure 15). The interaction between column and age was significant ( $p=0.037$ ). Both age groups were slower to respond to warnings in the periphery than to warnings in the center. However, older drivers had an additional tendency to be slower in responding to warnings on the right. In fact, their fastest column was 5 degrees to the left of the center (column B).

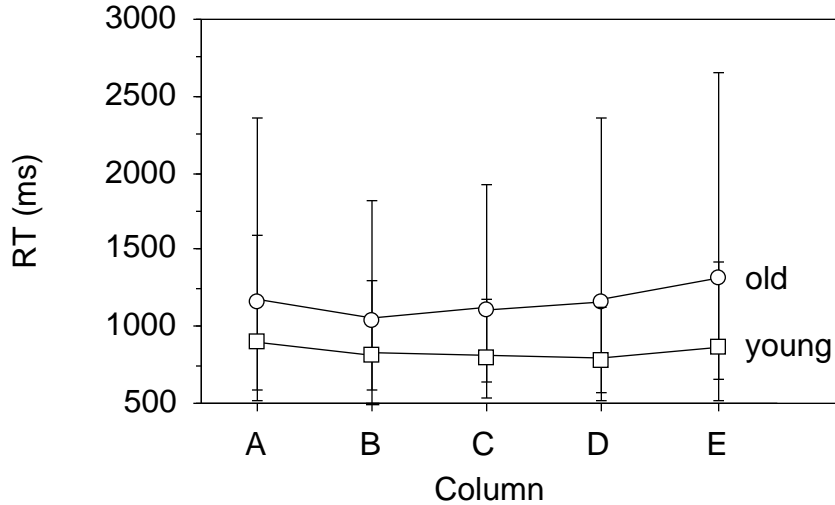


Figure 15. Effect of horizontal location and age on HUD response time

While younger drivers did not show a significant difference due to row, older drivers did (Figure 16). Their mean response time to warnings at eye level (row 2) was 1022 ms in comparison to 1304 ms at 5 degrees above eye level (row 1) and 1148 ms at 5 degrees below it (row 3). The interaction between row and age was significant ( $p=0.038$ ). This seems to be consistent with the eccentricity effect discussed earlier.

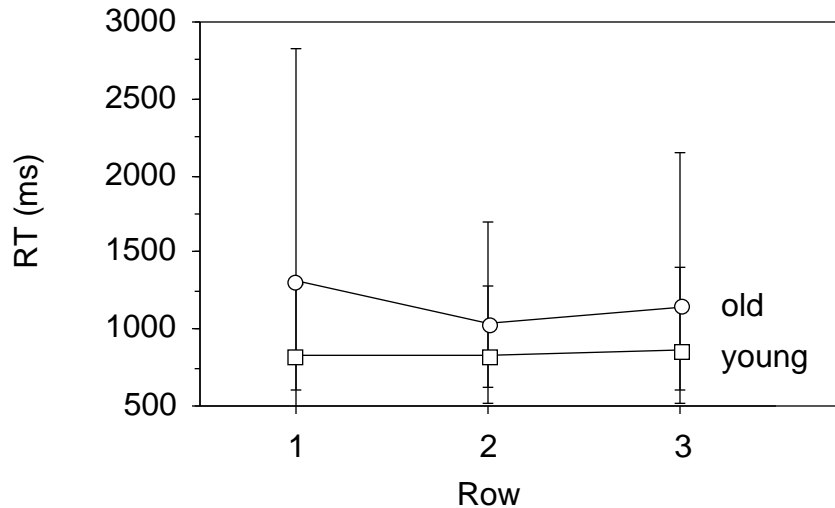


Figure 16. Effect of vertical location and age on HUD response time

Learning effect

Response time to HUD warnings decreased as the experiment progressed. Even though the magnitude of change was not very large (improvement of 40 ms per run) it was a significant change ( $p=0.0005$ ). In addition to the decrease in response time, there was a decrease in variance (Figure 17) as expected.

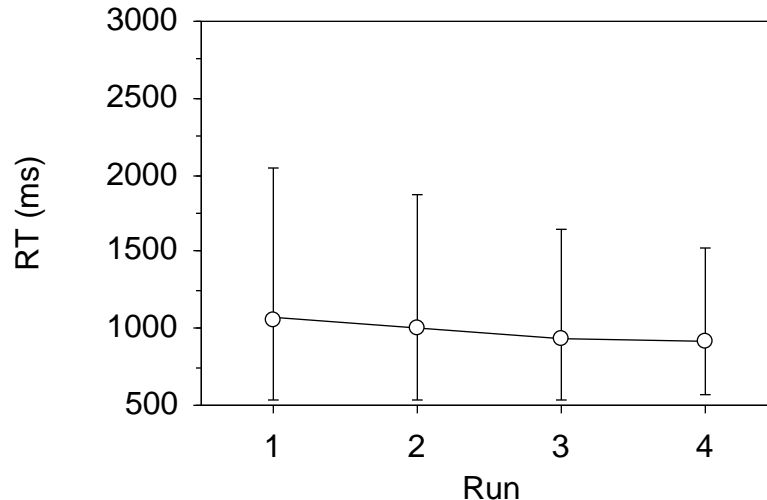


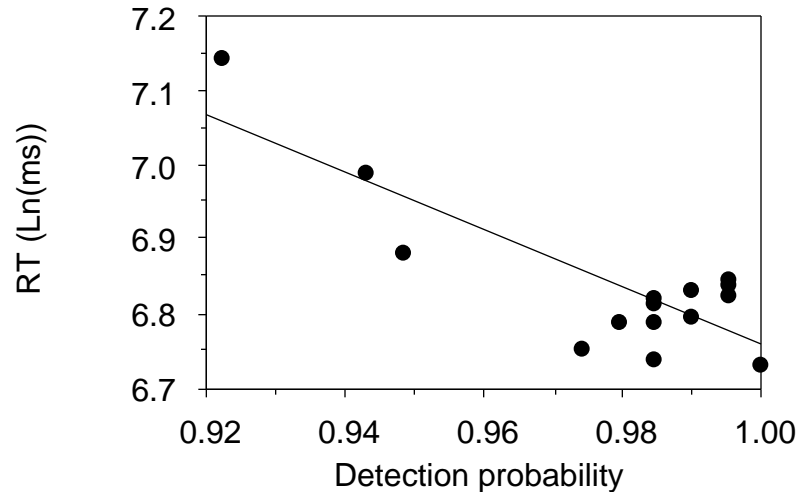
Figure 17. Learning effect on HUD response time

### Trial effect

Each driver was presented with two occurrences of the 15 HUD warnings for each road. These occurrences were compared to explore learning and fatigue effects. The trial effect was marginally significant ( $p=0.076$ ). Subjects responded faster to the first half of warnings than to the second half (934 ms, 1020 ms respectively). A figure illustrating the trial effect can be found in Appendix G.

### Correlation between detection probability and response time

Figure 18 shows the correlation between the transformed response times and the detection probabilities for the 15 different locations. Most locations had an average response time of approximately 950 ms and a detection probability over 0.95. There was a negative correlation (-0.93) between response time and detection probability. For example, D2 had a brief response time (of 842 ms) and a detection probability of 1.00 while E1 had a long response time (of 1390 ms) and a detection probability of 0.85. Thus, there was an inverse relationship between the two. The lower the detectability of a warning, the greater its average response times. A linear regression of the transformed response times was performed (keeping in mind that this relation does not necessarily imply causality). Note that for the subset of data points whose detection probability was over 0.97, there was almost no correlation.



Response time (Ln (ms)) = 10.65 – 3.894 \* detection probability + error  
 $R^2 = 0.70$

Figure 18. Correlation between HUD detection probability and response time

Effect of different roads and scenarios driven

An additional ANOVA was run with the road number as a factor. The road factor was significant ( $p=0.013$ ). Average response times to HUD warnings for road 1 through 4 were 976 ms, 978 ms, 1041 ms, and 911 ms respectively. The differences between roads were not very large and did not indicate any consistent trend. Since roads 1 and 3 were taped on the same section of US-23 N, the relatively higher response time for road 3 should probably be attributed to slight differences in traffic and in the sequence of events. The same holds true for roads 2 and 4 (US-23 S).

Detection probabilities for the different roads showed a slightly different effect. Average detection probabilities for roads 1 through 4 were 0.833, 0.868, 0.854, and 0.878 respectively. Detection probability for roads 1 and 3 was lower than that of roads 2 and 4.

**HUD warning detection with and without driving**

HUD baselines

Before and after the four main runs, subjects were presented with HUD warnings while the road scene was static to obtain as pre-experiment baseline and post-experiment baseline data. These baseline runs were used to test for interference due to the addition of driving and event-detection tasks. They were also used to test for learning or fatigue effects by comparison to each other.

As seen in Figure 19, there was a slight increase in average response time from 515 ms in the pre-experiment baseline to 566 ms in the post-experiment baseline ( $p=0.058$ ).

## Results

Although drivers had to respond to 120 HUD warnings between the two baseline tests, their response time in the post-experiment baseline did not improve. Fatigue and boredom are the most probable reasons for the slight increase in response time.

There was a large increase in response time when driving was performed with the HUD warning detection task. The average response time without a driving task was 540 ms in comparison to 976 ms for the HUD warning detection task while driving and detecting other events. As expected, this difference was extremely significant ( $p < 0.0001$ ) (see Table 22 in Appendix G).

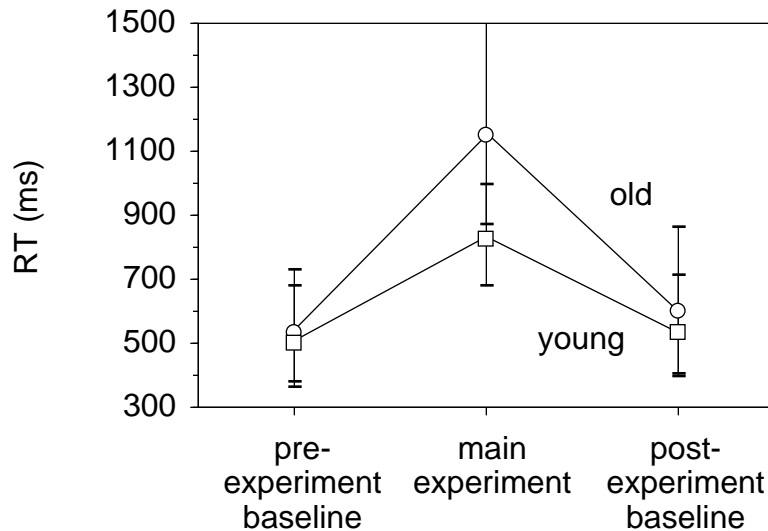


Figure 19. HUD response time during the main experiment and during the baselines

Figure 20 shows HUD response time as a function of horizontal location in the baselines and in the main experiment. Average response time was approximately 80 percent higher when drivers were performing the driving task. The U-shaped pattern, due to higher response times to warnings that were farther from the center, was only present in the main experiment but not in the baselines. The pre-experiment baseline had no significant trends related to horizontal location, while the post-experiment baseline had a slightly higher (but not statistically significant) response time for locations on the far right. This asymmetry may have been a by-product of performing the driving task for an hour and thus changing one's glance behavior correspondingly.

These differences in patterns of response time due to the addition of a driving task is of a practical concern to future experiments. If this experiment had been run without a driving task (as in baselines), response times would not only have been lower, but their pattern across locations would have been different. This difference in patterns suggests that future studies should consider driving demands in addition to HUDs.

## Results

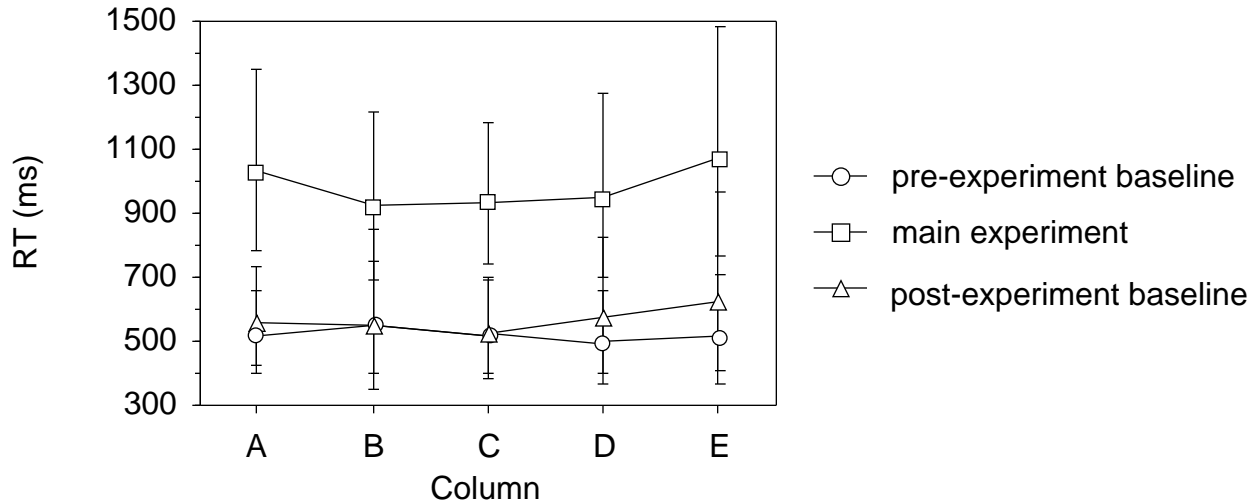


Figure 20. HUD response time as a function of horizontal location during the main experiment and during the baseline

### Luminance contrast

The experimental design of this study did not allow testing for illumination contrast effects as an independent factor. In fact, contrast was confounded with the location of HUD warnings. For example, HUD warnings in the upper left had an average contrast of  $1.5 \pm 0.1$  due to bright sky in the background. On the other hand, HUD warnings in the lower right had an average contrast of  $3.0 \pm 1.0$  due to a dark background of road or bushes. An attempt to regress response time to HUD warnings with their contrast resulted in no significant effect (Figure 21). There was no tendency for response time to increase or to decrease as a function of contrast. In fact, the rightmost data point in the graph represents a contrast of 6.47 with a transformed response time of 6.78 (883 ms), while the data point next to it represents a contrast of 5.67 with a transformed response time of 7.42 (1674 ms). The difference in response time between these two points cannot be explained by difference in contrast, but can easily be explained by their location. The higher response time point belongs to E1 and the other point is D2 (incidentally, these two points represent the fastest and the slowest point in the study).

An additional attempt to investigate contrast effect was made by examining the contrast for each location separately. However, very low R squared values were achieved ( $< 0.10$ ) and there was no consistent trend across different locations. As mentioned earlier, this study was not intended to investigate contrast effects, and therefore, it was hard to separate them from the more salient effects that were studied.



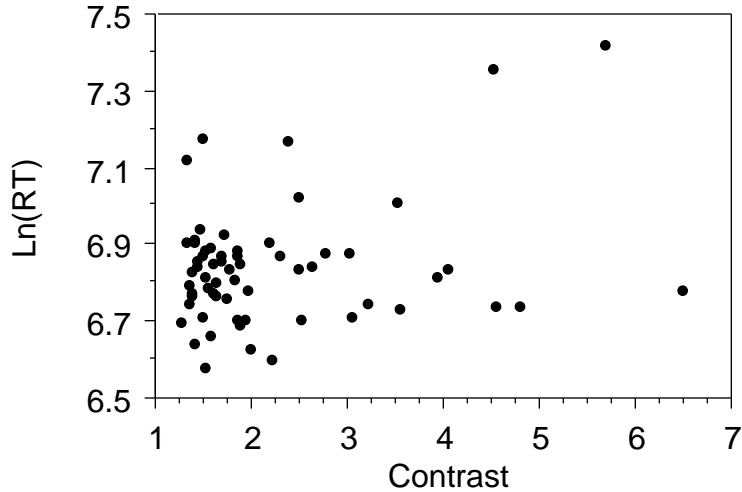


Figure 21. Response time (transformed) as a function of contrast level

**Responses to car signal lights**

Responses to signal lights of the leading vehicle were analyzed in a repeated measures ANOVA, which included age and gender as between subject factors and run as a single within subject factor (see Table 23 in Appendix G). Only age ( $p=0.007$ ) and run ( $p=0.004$ ) were significant. Younger subjects had an average detection probability of 0.92, while older subjects had an average detection probability of 0.81. There was an improvement in detection probability until run 3, and then a drop in the last run (Figure 22). Differences in response time as a function of run were not significant.

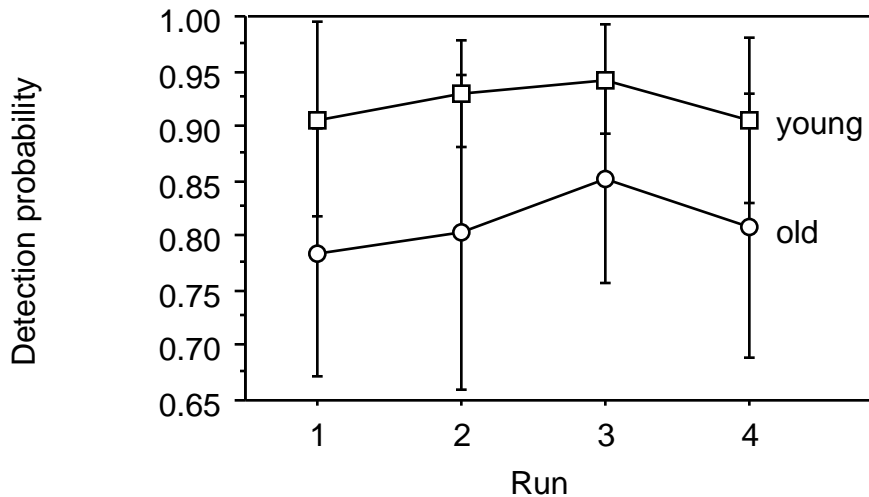


Figure 22. Effect of age and run on car signal lights detection probability

As can be seen in Figure 23, response time to car signals varied between roads. Road effect ( $p<0.0001$ ) and age effect ( $p=0.02$ ) were significant. Older drivers responded approximately 20 percent slower (1176 ms) than younger drivers (991 ms). The difference in response time between different roads was due to the amount of traffic and

## Results

other events and the timing of events. This observed difference between roads justifies the decision to randomize the order of roads across subjects.

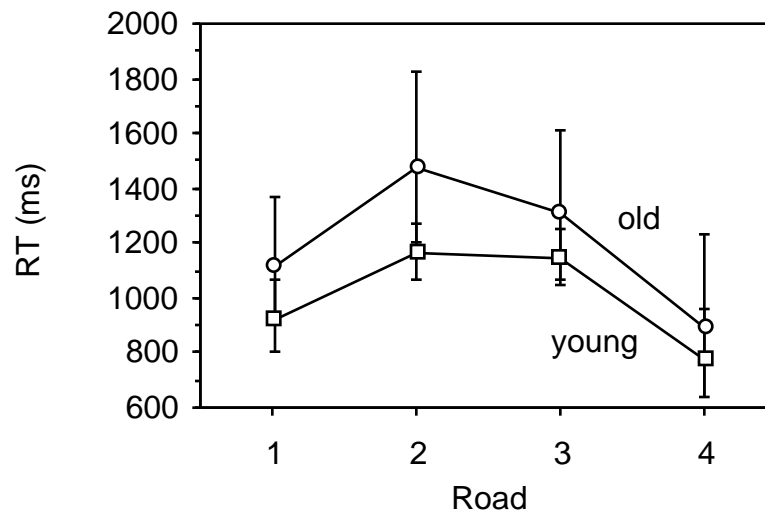


Figure 23. Effect of age and road on road event response time

### Effect of age and HUD task on car signal lights detection probability

To capture the interference due to presenting HUD warnings to the driver while driving, a comparison between baseline response time to car signals with and without presentation of HUD warnings was made. Response time did not change significantly between the two conditions. Average response time slightly decreased from 1200 ms before the main experiment to 1150 ms after it. Response time during the same segment of road while HUD warnings were presented was 1260 ms, which was less than 10 percent higher but not statistically different.

A significant change in the detection probability was observed between the baselines. Order effect between pre-experiment, main, and post-experiment was marginally significant ( $p=0.055$ ), and the interaction between this order and age was significant ( $p=0.017$ ) (see Table 24 in Appendix G). Older drivers kept improving their detection probability throughout the experiment from 0.80 in the pre experiment baseline to 0.88 in the main experiment (HUD warnings present) to 0.90 for the post-test baseline. Figure 24 presents the interaction between age and order in detection probability with and without HUD warnings presented. A post hoc Fisher's test did not find a significant difference between the post-experiment baseline and the main experiment, suggesting that detection probability did not significantly suffer from the addition of HUD warnings.

It is important to note that these measures are observations of the average detection probability and average response times. It is more than likely that at the exact time a warning was presented, car signals may have been missed due to simple obstruction. However, since the warning disappeared as soon as it was detected, the obstruction

## Results

was usually not long enough to affect the average response time and average detection probability of car signal events

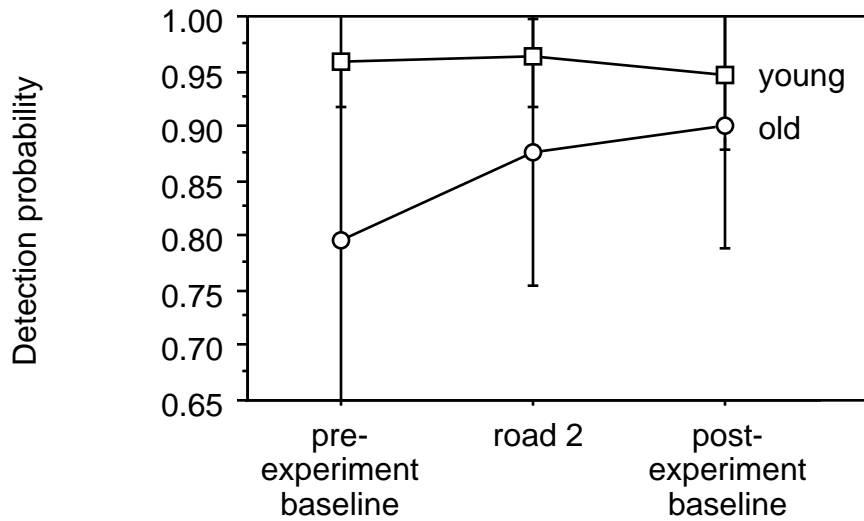


Figure 24. Effect of age and HUD task on car signal lights detection probability

### Detection probability of road events

Road events other than car signals included passing cars on the left side and road signs on the right side. Since it was not possible to precisely define when these events occurred, only detection probability was recorded. Figure 25 shows the detection probability for each of the 4 roads driven as a function of age. Older drivers averaged 0.83 while younger drivers averaged 0.89. This age difference was statistically significant ( $p=0.036$ ). The difference between roads was significant ( $p=0.023$ ) (see Table 25 in Appendix G). However, road order was counterbalanced between subjects, and no significant run effect was found.

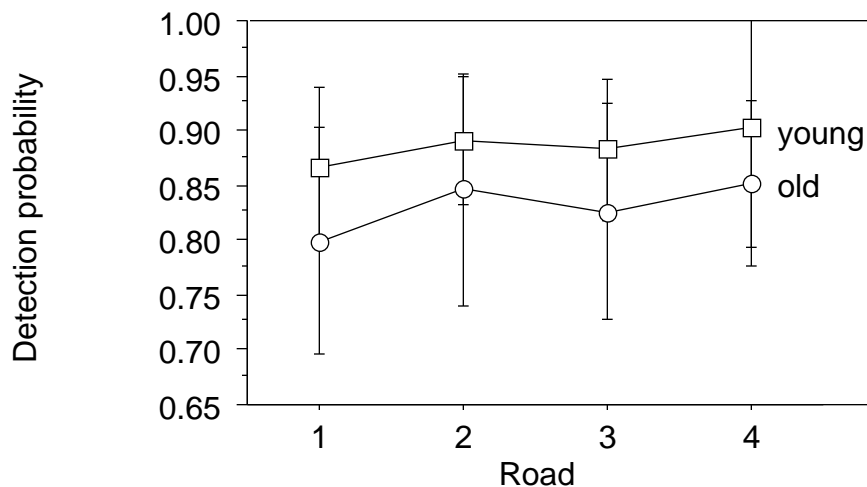


Figure 25. Effect of age and road scenario on detection probability of road events

## Results

### Learning effect in detecting road events

Comparison of detection probability for road events showed a slight, but not significant ( $p=0.73$ ) improvement between the pre-experiment baseline and the post-experiment baseline. Detection probability was 0.73 in the pre-experiment baseline, 0.72 during the experiment, and 0.72 in the post-experiment baseline. This lack of improvement suggests that some of the signals and events were hard to detect and could probably not be learned without repetition of the same scenario. It should be noted that the road signs were sometimes hard to see and that some drivers (especially older drivers) indicated that they concentrated less on the right side of the road.

### Subject preferences

After the experiment, subjects were asked to choose the three best and three worst locations for HUD warnings. Figure 26 shows the sum of all subjects' responses for the worst locations for a HUD warning. The least disliked locations were B1, C1, D1, A2, B2, D2, E2, B3, and D3.

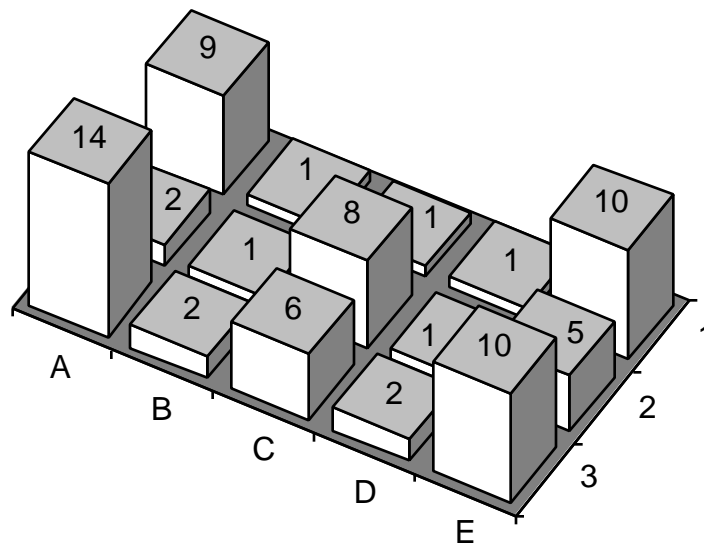


Figure 26. Subject responses for "worst" locations for a HUD

Figure 27 shows the sum of all subjects' responses for the best locations for HUD warnings. A Kruskal-Wallis test was performed across. The columns were significantly different ( $p=0.028$ ) with column D being the favorite, followed by columns C, B, E, and A.

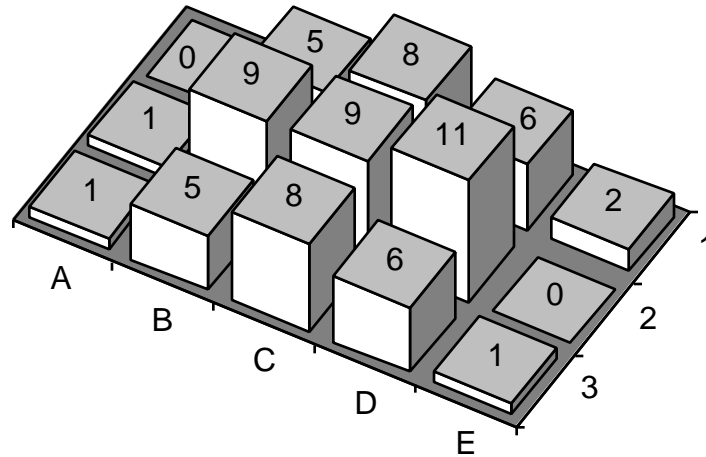


Figure 27. Subject responses for "best" locations for a HUD

Figure 28 shows the net result of the best and worst locations for a HUD. A Kruskal-Wallis test revealed that the columns were significantly different ( $p=0.027$ ) with column D being the favorite, followed by columns B and C. Columns A and E had net values below zero.

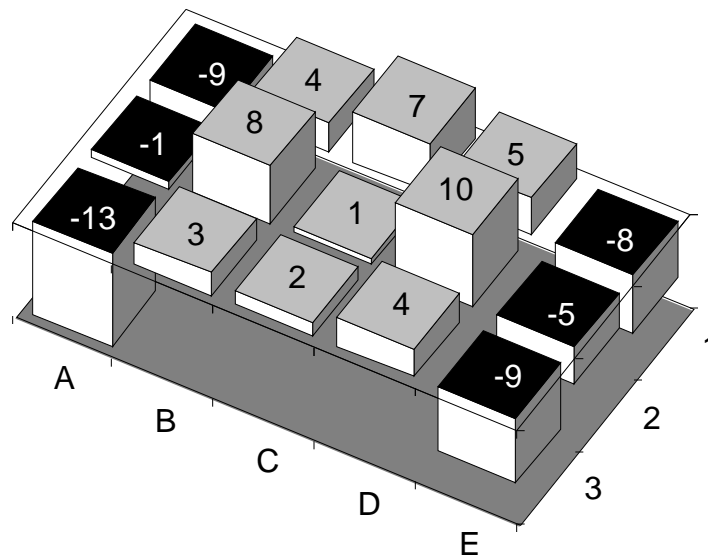


Figure 28. A sum of "best" and "worst" locations

### Subjective evaluation

#### Evaluation of the HUD

Subjects rated the difficulty in detecting HUD warnings, the interference of HUDs with road events, and the potential usefulness of HUDs for drawing attention. Subjects rated on a visual-analog scale which was then converted to a six-point scale. Table 6 shows the mean and standard deviation of the subjects' rating of the HUD.

Table 6. Evaluation of the HUD

	Mean	SD
<b>Difficulty</b> in detecting warning triangles (1 = very easy to 6 = very difficult)	1.1	0.7
<b>Interference</b> of warning triangles with detecting road events (1 = not interfering to 6 = most interfering)	2.0	1.3
<b>Usefulness</b> of warning triangles to draw attention (1 = not useful to 6 = most useful)	5.1	1.0

Evaluation of the task

Table 7 shows the mean and standard deviation of the subjects' rating of task difficulty. In this case, the difficulty of the combined task was equal to the sum of the component ratings, (2.0 + 1.2 = 3.2), that is, task difficulties were additive as expected.

Table 7. Evaluation of the tasks (1 = easy, 6 = difficult)

	Mean	SD
Driving only	2.0	1.2
HUD only	1.2	0.5
Driving and HUD	3.2	1.3

Simulation Fidelity

Twelve of the 24 subjects reported at least some similarity of the simulation to real driving with comments such as the following: "visually same," "lifelike," "quite similar," "rather similar," "about the same." The subjects also reported many differences between the simulation and real driving. Some of the comments attesting to the difference were the following: "different seating position," "more aware in real driving," "concentrated more for test," "easier than real driving," "more distracting," "I drive faster," "harder to see brake lights."

Rank order of priority of events

Subjects ranked their priority of detecting the four events during the experiment. Seventeen of the 24 subjects ranked taillights as the highest priority. Twelve ranked taillights and passing vehicles as their two highest priorities. Seventeen ranked road signs as the lowest priority. Twelve chose road signs and HUD as the two lowest priorities.



## CONCLUSIONS

The primary objective of this study was to identify the best location to display information on HUDs so as to minimize potential interference with driving. More specifically, the study empirically examined the effect of HUD location on objective and subjective measures.

### **Does location affect response time and detection probability of HUD warnings?**

As expected, the response times to HUD warnings, and to a lesser extent, to detection probability, were different depending on HUD location. The average response times ranged from 842 ms to 1390 ms. The detection probability for most locations (12 of 15) was 0.97 or higher. Detection probability was highly correlated with response times. The locations with lower response times had higher detection probabilities.

It was expected that locations farthest from the line of sight would have the slowest response times and lowest detection probability. Only two upper-right (D1, E1) and one lower-left (A3) locations met this expectation. The other locations were not significantly different from each other in response time or in detection probability. However, when comparing locations by rows, responses to warnings in the middle row were significantly faster than the other rows. Likewise, when comparing locations by columns, responses to warnings in the 3 center columns were significantly faster than the outside columns.

While response times and detection probability of center locations were generally similar, the fastest response time was located 5 degrees to the right of the center (D2).

In the repeated measures analysis, age was a significant factor. An estimation of an acceptable response to a HUD warning is no more than 2 - 3 seconds. Ten percent of older subjects' responses were over 2827 ms while only 3 percent of younger subjects' responses were over this value.

The eccentricity effects were extenuated for older subjects. Older subjects took longer and more frequently missed the HUD warnings in the corners. The interaction effects between age and column, as well as age and row were significant. The eccentricity effect may have been a result of differences in eye fixation patterns and field of view of older subjects (e.g., mainly looking at the lead vehicle and therefore missing some HUD warnings in the periphery).



### **Does the presence of a HUD (1) interfere with the detection of and (2) alter response time to events on the road?**

There are two interference issues: (1) HUDs interfering with detecting road events and (2) road events interfering with responding to HUD warnings.

Interference of HUDs with detecting road events is more important for practical purposes. If appearance of a HUD warning interferes with detecting road events, it may not be worthwhile to use HUD warnings at all. Although it is reasonable to assume that some interference occurred, response times and detection rate to events on the road were not significantly worse when the HUD detection task was performed concurrently. Therefore, the presence of a HUD does not interfere with the detection and response time to events on the road.

However, several caveats should be kept in mind. First, subjects in the study were not actually controlling the vehicle. Even though they were asked to perform steering movements, their workload was probably lower than when actually driving a motor vehicle. Second, subjects were alert for HUD warnings, thus reducing the effect of surprise. Third, HUD warnings occurred rather frequently (interval times were between 21 and 29 seconds) far more than in real driving, but a practical experimental necessity. Finally, when subjects recognized that a HUD warning was present, the warning disappeared as soon as they responded. This prevented immediate obstruction, and may not be the case in real-world situations.

The interference of road events with responding to HUD warnings may not have a large practical impact on driving. However, it has importance regarding future experiments. The results indicate that there is a difference between responding to only HUDs and responding to HUDs in a driving context. When the road event detection task was added, the pattern of responses across horizontal locations changed due to the interference of road events. Therefore, it is suggested that future HUD experiments always be conducted in a driving context.

When the road-event detection task was added to the HUD detection task, older subjects were more susceptible to the interference. This is probably due to overload of the older subjects.

### **What are the best and worst locations for a HUD as reported by the subjects?**

Subjects were asked to point out the best 3 locations and worst 3 locations of HUD warnings after 2 hours of the experiment. Their responses matched the eccentricity assumption. The corner locations were perceived by many subjects to be worse than central locations. There was also a strong tendency to dislike the center location and the lower center. It was not surprising that each location was voted by at least one subject as the worst location. In other words, no matter where the HUD is positioned, the location will not please everyone all the time.

## **Conclusions**

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The subjective preferences should be treated cautiously due to the small number of data points. Drivers did not like locations that were farther than 5 degrees horizontally from the center and preferred locations where less overlapping with important events occurred (e.g., in the exact center).

Interestingly, if one location were to be chosen, it would be the same location that was chosen for the objective measures. HUD warnings located 5 degrees right of the center (D2) were slightly preferred over warnings located symmetrically to the left of the center.



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## APPENDIX A - Tabular Review of the HUD Literature

As was noted in the introduction, Tables 8-12 provide a summary of the literature relevant to automotive HUDs grouped by dependent measure type (performance vs. subjective) and context (aircraft, automotive). Within each table, studies are grouped by experiment. For each experiment details on subjects, independent and dependent measures, tasks, and outcome are provided. A summary or concluding comment is provided for each table as well.

Table 8. Studies concerning the general benefits of automotive HUDs

Author(s), Year	Methods	Results
Flannagan and Harrison (1994)	<p><u>Subjects</u>: 24 (12 ages 18-25, 12 ages 60-74)</p> <p><u>Task</u>: Subject was shown a slide of a road scene for 30 ms with a superimposed HUD and said the direction of the final turn followed by saying if a pedestrian was in the scene</p> <p><u>Independent variables</u>: HUD angle (4, 9, 15 degrees below horizon), task (road or HUD), driver age</p> <p><u>Dependent variables</u>: Error rate in identifying the presence of a pedestrian in a road scene (yes or no); error rate for final turn direction on a simulated map (left or right)</p>	<p>Error rates for older drivers were about 24% versus 12% for younger drivers. As the HUD angle increased, error rates on the pedestrian task increased sharply (from 10% to 30%), while error rates in the HUD task declined (from about 18% to 14%). There were interactions with age, task, and HUD position.</p>

Author(s), Year	Methods	Results
Fukano, Okabayashi, Sakata, and Hatada, 1994	<p><u>Subjects</u>: 2 men: 1 in 20s, 1 in 30s</p> <p><u>Primary task</u>: Subject was shown either a black circle or a black square in their forward field of view (50 m away) and pressed a button if the circle appeared.</p> <p><u>Secondary task</u>: Subject was shown a big circle and a little circle on a screen and put the little circle into the big circle using keyboard switches.</p> <p><u>Independent variable</u>: Location of display system for secondary task: 10 degrees below center of forward field of view, 40 degrees below forward field of view at the center of the car</p> <p><u>Dependent variables</u>: Performance scores on primary and secondary tasks</p>	Performance scores for both the primary and secondary task were higher when the display was at 10 degrees below the center of the forward field of view.
Kiefer and Gellatly, 1996.	<p><u>Subjects</u>: 36 licensed drivers: 12 young (ages 16-24), 12 middle-aged (35-53), 11 older (59-71)</p> <p><u>Task 1</u>: Verbally identify speedometer digits</p> <p><u>Task 2</u>: Verbally identify speedometer digits and read distant speed limit sign</p> <p><u>Task 3</u>: Verbally identify speedometer digits and report presence of any hazard or surprise target</p> <p><u>Task 4</u>: Verbally identify speedometer digits and report the presence of a pedestrian</p> <p><u>Independent variable</u>: Location of speedometer display: HUD vs. head-down display (HDD)</p> <p><u>Dependent variable</u>: Accuracy of task completion</p>	<p><u>Task 1</u>: No main effect of display type</p> <p><u>Task 2</u>: When subject underwent the HUD condition before the HDD condition, task performance was better with the HUD.</p> <p><u>Task 3</u>: Subjects were better able to detect 5 of 10 surprise targets when using the HUD as opposed to the HDD. Differences were not significant for the other targets.</p> <p><u>Task 4</u>: Young and middle-aged subjects were better able to detect a pedestrian with the use of the HUD as opposed to the HDD. Benefits of the HUD were not clearly apparent in the case of the older subjects.</p>
<p><u>Comments</u>: Based on the results of the aforementioned studies, HUDs improve the driver's ability to access display information while viewing the forward scene. The safety implications of these findings illustrate the benefits of implementing HUDs in motor vehicles.</p>		

Table 9. Studies illustrating the benefits of placing HUDs in the normal line of vision

Author(s), Year	Methods	Results
Iino, Otsuka, and Suzuki, 1988	<p><u>Subjects</u>: Not reported</p> <p><u>Task</u>: Subjects drove a vehicle at different speeds and observed the HUD once every 10 seconds.</p> <p><u>Independent variables</u>:</p> <ol style="list-style-type: none"> <li>1. display type (HDD or HUD)</li> <li>2. HUD location (centered in forward field of view, 10 degrees to the left, or 20 degrees to the left)</li> <li>3. speed of vehicle (60 to 100 km/h, increments of 10 km/h)</li> </ol> <p><u>Dependent variable</u>: Driver's reading time of display (measurement details not specified)</p> <p><u>Location of experiment</u>: Tomei Expressway, Japan</p>	<p><u>Main effects of display type</u>: Reading times were shorter for HUDs than for HDDs in all conditions.</p> <p><u>Interaction between HUD location and vehicle speed</u>:</p> <ul style="list-style-type: none"> <li>• For speeds &gt;70 km/h, reading times were shorter when HUD was centered. They were slightly longer when the HUD was located 10 degrees to the left and still longer when the HUD was 20 degrees to the left of the forward line of vision.</li> <li>• For speeds &lt;70 km/h, there was no correlation between reading times and HUD location.</li> </ul>



Author(s), Year	Methods	Results
Isomura, Kamiya, and Hamatani, 1993	<p><u>Subjects</u>: 2 average-skilled drivers (ages 28 and 32), 1 novice driver (age 23)</p> <p><u>Task</u>: Subjects in a cockpit watched videotaped scenes of a road. To control the scene speed, they pressed the brake pedal or the accelerator. Subjects were given two central tasks and one peripheral task.</p> <p><u>Central task 1</u>: Random marks (red and blue circles and squares at a visual angle of 1 degree) appeared in the subjects central field of view and subjects pressed a button every time two identical marks appeared one after the other.</p> <p><u>Central task 2</u>: Subjects depressed the accelerator as necessary to maintain a certain target speed. The target speed as well as the virtual vehicle speed were shown on a digital display in the subjects central field of view.</p> <p><u>Peripheral task</u>: Subjects pressed a button when they noticed a peripheral mark. (Marks appeared at one of the angles approximately every three seconds.)</p> <p><u>Independent variable</u>: Viewing angle of peripheral cue (40, 30, or 10 degrees to the left of the forward field of view)</p> <p><u>Dependent variable</u>: Task</p>	<p>Peripheral task accuracy increased as the viewing angle decreased. The central task accuracy was virtually the same for all viewing angles. Within each viewing angle, there was a tradeoff between central task accuracy and peripheral task accuracy. That is to say that when more attention is devoted to the central task, performance on the peripheral task declines and vice versa.</p>

Author(s), Year	Methods	Results
Okabayashi, Sakata, Furukawa, and Hatada, 1990	<p><u>Subjects</u>: 7 licensed drivers (men, ages 24-42)</p> <p><u>Task</u>: Subjects viewed a screen (5 m away) on which different Snellen figures appeared. The Snellen figures appeared at an area that ranged from 15 degrees to the right and left of the subjects forward field of vision. The HUD was an image of random two digit numbers (0.8 m away). Subjects verbally indicated the direction of the Snellen figure and read the digits on the HUD.</p> <p><u>Independent variable</u>: position of HUD relative to the angle of depression from the normal line of vision (range: 0 to 20 degrees)</p> <p><u>Dependent variable</u>: Correct response rate</p>	Correct response rate increased linearly as HUD moved vertically closer to the normal line of vision.
<p><u>Comments</u>: These studies illustrate the benefits of having a HUD horizontally and vertically centered in the forward line of vision. However, these studies did not consider all the factors necessary to claim that the forward centered position is optimal for all HUDs. To determine the optimal position, a greater emphasis on the distraction effects of centered HUDs is required.</p>		

Given the potential interference of a centrally located HUD, subjective studies have been conducted to determine the annoyance associated with various HUD locations.

Table 10. Subjective studies illustrating the costs of placing HUDs in the normal line of vision

Author(s), Year	Methods	Results
Iino, Otsuka, and Suzuki, 1988	<p><u>Subjects:</u> 6 men (ages 20-40)  <u>Task:</u> Measurement details unspecified  <u>Independent variables:</u></p> <ol style="list-style-type: none"> <li>1. Display position (centered in forward field of view, 10 degrees to left, 20 degrees to left)</li> <li>2. Type of road (urban, expressway)</li> </ol> <p><u>Dependent variables:</u></p> <ol style="list-style-type: none"> <li>1. Masking of view range</li> <li>2. Absorption of viewpoint</li> <li>3. Annoyance</li> <li>4. Quality of viewing</li> </ol>	<p>For both road types, the quality of viewing was rated as “bad” when the HUD was at 20 degrees left. For both road types, the masking of the view range and the “absorption” of the viewpoint were rated as “bad” when the HUD was at 0 degrees. When the HUD was at 10 degrees to the left, all 3 variables were rated as “good” or “very good.”</p>
Weihsrauch, Meloeny, and Goesch, 1989	<p><u>Subjects:</u> Details unavailable  <u>Task:</u> In a dynamic simulation, subjects sat in a vehicle with a variable geometry HUD. Subjects indicated their preference for HUD location (participant and measures details unspecified).  <u>Independent variable:</u> HUD location  <u>Dependent variable:</u> Drivers’ location preference</p>	<p>The preferred location for a HUD was centered in the forward field of view, 8 degrees below the line of vision.</p>
<p><u>Comments:</u> These studies suggest that putting HUDs in the normal line of vision may not be ideal. Being strictly subjective, the performance implications of placing the HUD in the normal line of vision were not considered.</p>		

Table 11. Performance based studies illustrating the costs of placing HUDs in normal line of vision

Author(s), Year	Method	Results
<p>Foyle, McCann, Sanford, and Schwirzke, 1993</p>	<p><u>Experiment 1:</u>  <u>Subjects:</u> 14 right-handed men with normal or corrected eyesight.  <u>Tasks:</u>            1. Maintain altitude of 100 ft.            2. Follow delineated ground path. (All tasks conducted in flight simulator.)  <u>Independent variables:</u>            1. HUD condition: located 0 degrees from line of vision (lower portion of screen), 8.14 degrees from line of vision (center portion of screen), 16.28 degrees from line of vision (upper left portion of screen), no HUD. All HUDs contained altitude information.            2. Type of task (altitude or path)  <u>Dependent variables:</u>            1. Root Mean Squared Error (RMSE) for path            2. RMSE for altitude.</p> <p><u>Experiment 2:</u>  <u>Subjects:</u> 10 right-handed men with normal or corrected eyesight.  <u>Tasks and simulation :</u> Same as in experiment 1  <u>Independent variables:</u>            1. HUD condition: altitude indicator, irrelevant static indicator, irrelevant dynamic indicator, no HUD. All HUDs were positioned in the subject's line of sight.            2. Type of task (altitude or path)  <u>Dependent variables:</u> RMSE's for altitude and path</p>	<p><u>Experiment 1:</u>            RMSE for altitude was decreased by the presence of HUDs.            RMSE for path was significantly higher when the HUD was in the line of vision than when the HUD was absent or located elsewhere.</p> <p><u>Experiment 2:</u>            RMSE for altitude was again lower with the presence of the HUD for altitude.            RMSE for path was significantly higher when the HUD was present and displayed altitude. RMSE was hardly affected by HUD with irrelevant information.</p>

Comments: Though this study was conducted in a flight simulator, it has implications for driving. Experiment 1 indicated the potential problems with having a HUD in the normal line of vision. Experiment 2 determined if these problems were the result of visual masking. The lack of interference of the irrelevant data, however, suggests that the heightened RMSE's found in experiment 1 resulted from attentional tunneling rather than visual interference. In other words, having a display in the forward field of view that is relevant to one of the tasks caused subjects to focus too narrowly on that task, which, in turn, causes them to perform poorly on other tasks. The Foyle et al. study supports the subjective studies previously discussed.

Table 12. Studies involving both subjective and objective measures

Author(s), Year	Methods	Results
<p>Inzuka, Osumi, and Shinkai, 1991</p>	<p><u>Study 1: In-plane location</u>  <u>Part 1: Viewpoint distribution</u>  <u>Subjects:</u> 2 men accustomed to driving with an eye-mark camera.  <u>Task:</u> Eye fixations were recorded as the subjects drove an experimental vehicle on a straight expressway and an urban road.  <u>Independent variable:</u> Type of road (urban, expressway)  <u>Dependent variable:</u> Eye position</p> <p><u>Part 2: Annoyance of display</u>  <u>Subjects:</u> 6 men  <u>Task:</u> In the laboratory, subjects were told to focus on a target. A digital speedometer was placed at 32 different positions around the target, 1 m away from the eye. Subjects indicated the annoyance level of the speedometer on a 5 point scale.  <u>Independent variable:</u> Display position  <u>Dependent variable:</u> Subject's evaluation of annoyance</p>	<p><u>Viewpoint distribution:</u></p> <ul style="list-style-type: none"> <li>• <u>Expressway:</u> 90% of the fixations occurred in a rectangular area bounded at 4 degrees above and below, 11 degrees left, and 5 degrees right.</li> <li>• <u>Urban road:</u> 90% of the fixations occurred in a rectangular area bounded at 6 degrees above the line of vision, 5 degrees below, 12 degrees left and 11 degrees right.</li> </ul> <p><u>Annoyance of display:</u> A mean annoyance rating was calculated at every position. High levels of annoyance were found to be in a hexagonal area bounded at 8 degrees left, 7 degrees right, 5 degrees up, and 8 degrees down. Based on the combined results of the two parts of the study, Inzuka, et al. recommend that HUDs be located between 6 and 10 degrees below the line of vision and between 8 degrees to the left and 5 degrees to the right.</p>
<p><u>Comments:</u> This study goes into greater detail than the purely subjective studies concerning HUD location. It evaluates viewpoint distribution using eye fixation levels as the objective measure, but it also takes into account the subjective annoyance factors involved with putting the HUD in various locations. Based on the results of this study, the authors interpolated an optimal range for HUD location that both maximizes eye fixation levels and minimizes subjective annoyance ratings. These conclusions, it seems, provide a compromise between the location suggestions presented in Tables 1 through 4.</p>		

Tables 13 through 19 contain summaries of the literature concerning safety issues and image distance, size, color, luminance, and contrast. The literature suggests HUD images should appear to be 2.0 m or greater from the driver, just under 1 degree visual angle, with characters of at least 28 min of arc, and minimum luminance ratios of approximately 1.25:1 for daytime, 4:1 at night, both varying with environmental conditions. HUD display luminance should not exceed 3000 cd/m<sup>2</sup>.

Table 13. Studies illustrating the potential dangers of HUDs

Author(s), Year	Methods	Results
Wolffsohn, McBrien, Edgar, and Stout , 1998	<p><u>Subjects</u>: 8 young (19-24), 8 middle-aged (35-44), 8 older (49-74).  <u>Task</u>: to perform a HUD-assisted driving task and depress a foot pedal when specified changes occurred in HUD image or outside world scene (e.g., brake lights)  <u>Independent variables</u>:</p> <ol style="list-style-type: none"> <li>1. age</li> <li>2. level of cognitive demand involved in HUD task</li> </ol> <p><u>Dependent variable</u>: Response times to and detection rates of changes in HUD image or outside world scene</p>	<ul style="list-style-type: none"> <li>• As age increased, response times increased and detection rates decreased.</li> <li>• As cognitive demand of the HUD task increased, response times increased and detection rates decreased.</li> </ul>
<p><u>Comments</u>: This study raises questions about the safety implications of HUDs. Apparently, HUDs have the potential to reduce response times to road events. This effect is visible when drivers are old or when HUDs require increased cognition.</p>		

Table 14. Literature concerning optical distance and HUD safety

Reference	Recommendations and Conclusions
Tufano, 1997	Suggests that having HUDs at a near optical distance can lead to double vision and distance overestimation. Optical distance may also have influences on the detection of outside objects as well as the perception of the size of these objects. Thus, further research should be conducted on the effects of optical distance in order to gauge the influence of this factor on HUD safety.

Table 15. Studies concerning optical distance in flight simulations

Author(s), Year	Methods	Results
Weintraub, Haines, and Randle, 1985	<p><u>Subjects:</u> 18 men (ages 19-28), 7 of whom were pilots</p> <p><u>Task:</u> Using a flight simulator, subject landed an aircraft onto a runway. Subjects also viewed a HUD which indicated both altitude and airspeed. If the altitude or airspeed fell out of a given range, then the subject was to activate a switch. If the altitude and airspeed were within the given range, then the subject focused on the runway (at optical infinity) to see if it was open (indicated by a diamond on the runway) or closed (indicated by an X on the runway). Depending on the status of the runway, the subject had to press one of two switches.</p> <p><u>Independent variables:</u></p> <ol style="list-style-type: none"> <li>1. HUD distance: 0 diopters (optical infinity), 1 1/3 diopters, 4 diopters</li> <li>2. Viewing angle: straight ahead or 10 degrees down</li> <li>3. Level of luminance</li> </ol> <p><u>Dependent variable:</u> Reaction time to press the appropriate switch</p>	<p><u>HUD location:</u></p> <ul style="list-style-type: none"> <li>• Reaction times for landing decisions were fastest when the HUD was at an optical distance of 0 diopters.</li> <li>• Reaction times were the same when the display was at 1-1/3 diopters 10 degrees down or 1-1/3 diopters straight ahead.</li> </ul> <p><u>Luminance:</u> In all cases, reaction times were slightly less in the higher luminance conditions.</p>
<p><u>Comments:</u> Since reaction times were slower when subjects had to change their focus, accommodation time should be a concern in the placement of HUDs. Though this study concerns flight simulation, its implications concerning accommodation can be applied to driving as well.</p>		



Table 16. Studies concerning image distance in automotive simulations

Author(s), Year	Methods	Results
Inzuka, Osumi, and Shinkai, 1991	<p>Study 2: Distance</p> <p><u>Subjects</u>: 4 younger (ages 20-29), 10 older (ages 50-70)</p> <p><u>Task</u>: Focus on lamp 10 m away, then read speedometer display and press button.</p> <p><u>Independent variable</u>: Distance of speedometer from eyes: 0.8, 1.5, 2.0, 2.5, 5.0 m</p> <p><u>Dependent variable</u>: Display recognition time (time before depression of button)</p>	<p>For older subjects, recognition times decreased significantly when the display distance went from 0.8 m to 2.5 m from the subjects' eyes. Recognition times leveled off at distances greater than 2.5 m.</p>
Kato, Ito, Shima, Imaizumi, and Shibata, 1992	<p>Similar method to that of Inzuka et al.</p> <p><u>Subjects</u>: Some older and some younger (details unspecified)</p> <p><u>Task</u>: Gaze at road surface 10 m ahead and then read display (details unspecified)</p> <p><u>Independent variable</u>: Distance of display</p> <p><u>Dependent variable</u>: Image recognition time (measurement details unspecified)</p>	<p>Results mirrored those of Inzuka et al. (above), yet a distance of 2 m was suggested.</p>
<p><u>Comments</u>: The results suggest that older people need more time to readjust their focus. The implications are that it would be beneficial to place HUD images at a distance close to the driver's focal distance. The results of these studies differ slightly from the results of the Weintraub et al. study (1984) concerning landing an aircraft in that the driving studies did not suggest that HUDs be placed at optical infinity. A major concern with putting the HUD further ahead is that drivers may not see objects immediately in front of them if they focus on a point too far ahead.</p>		

Finally, the literature contains a number of documents that consider display size, display color, and display luminance contrast. Those listed here should be considered the most important ones relating to automotive applications.

Table 17. Studies concerning size

Author(s), Year	Methods	Results
Inzuka, Osumi, and Shinkai, 1991	<p><u>Subjects</u>: 7 males  <u>Task</u>: Subjects evaluated legibility of sample compared with instrument panel display and selected the most legible sample.  <u>Independent variables</u>:            1. Size of HUD: 20-40 mm            2. Display distance  <u>Dependent variable</u>: Subject's evaluation of legibility</p>	<p>Optimal sizes (visual angles) were different for each display distance.            For a display distance of 2.5 m, the display was rated the most legible when it had a visual angle of 0.8 degrees.            When the display was 2.0 m away, 0.9 degrees was rated as the optimal visual angle.</p>
Kato, Ito, Shima, Imaizumi, and Shibata, 1992	Same variables as aforementioned study (details unspecified)	Support the findings of Inzuka et al.
Reference	Recommendations	
Weintraub and Ensing, 1992	HUD State of the Art Report (SOAR) recommends that there be a visual angle of at least 28 min for alphanumeric information and a visual angle of 34 min for symbols. The character width is recommended to be 75 percent that of character height.	

Table 18. Literature concerning color

Reference	Recommendations and Conclusions
Weintraub and Ensing, 1992	Color should not be used for HUDs. HUDs should be monochromatic with a narrow band phosphor.
Inzuka, Osumi, and Shinkai, 1991	Based on a study on (1) color contrast between display and foreground and (2) color sensitivity vs. brightness of display, Inzuka, et al. recommended that HUDs should be green. Details of this study are not specified.
Semple, Heapy, Conway, and Burnette, 1971; also Weintraub and Ensing ,1992	If color is used, blue and red should be avoided because blue is hard to focus on and red is not night vision compatible.

Table 19. Literature concerning luminance and contrast

Reference	Recommendations and Conclusions
Weintraub and Ensing, 1992	Luminance contrast ratios range from 1.15:1 to 1.5:1 for daytime conditions. At nighttime, a ratio of 4.0/1.0 should be used.
Okabayashi et al., 1990	For complex images, luminance contrast ratios should be no greater than 1.2/1.0.
Kato et al., 1991	HUD display luminance should not surpass 3000cd/m <sup>2</sup> .
Harrison, 1994	Given that recommended luminance contrast ratios vary with environmental conditions, there is no one appropriate contrast ratio.

**APPENDIX B - Consent Form**

**SUBJECT CONSENT FORM  
for Head-Up Display (HUD) Study**

The purpose of this experiment is to examine driver behavior while using a head-up display. A HUD presents information on the windshield so that the information appears superimposed on the scene ahead. Commonly used in aircraft to show essential information such as airspeed and altitude, these displays allow operators to focus their attention on the scene ahead, a potential safety benefit. There is a considerable interest in using HUDs to present navigation guidance and warning information to drivers, as well as for other purposes. However, in the process of doing such, there is a concern that the added information may interfere with the ability to detect other road events.

Several objects (to be described later) will appear either on the road scene or on the HUD to which you will respond by pressing buttons. You will be videotaped throughout the duration of the experiment for analysis purposes.

The entire study will take approximately 2 hours to complete. You will be paid \$35 upon completion of the experiment.

Some people experience motion discomfort in the simulator. If this occurs, tell the experimenter immediately, and he/she will stop the experiment. You can withdraw from the study at any time and for any reason. You will be paid regardless.

If you have any questions, please do not hesitate to ask the experimenter at any time.

Thank you for your participation.

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*It is ok to show segments of my test session in presentations to UMTRI visitors, UMTRI papers and reports, and on conferences and meetings. (This is not required for participation in the study but is useful to have. Your name will not be mentioned.)*

*I agree \_\_\_\_\_ I disagree \_\_\_\_\_*

-----

I have reviewed and understand the information presented above. My participation in this study is entirely voluntary.

\_\_\_\_\_  
Subject Name (PRINTED)

\_\_\_\_\_  
Date

\_\_\_\_\_  
Subject Signature  
Investigator: Paul Green 763-3795

\_\_\_\_\_  
Witness (experimenter)



## APPENDIX C - Biographical Form

<b>University of Michigan Transportation Research Institute</b> <b>Human Factors Division</b>	Subject: <input style="width: 100%;" type="text"/>
<b>Head Up Display Study Biographical Form</b>	Date: <input style="width: 100%;" type="text"/>
Name: _____	
Male    Female (please circle)      Date of Birth: <u>   /    /   </u> <span style="margin-left: 400px;">mm / dd / yy</span>	

**What kind of motor vehicle do you drive the most?**

make: \_\_\_\_\_      model: \_\_\_\_\_      year: \_\_\_\_\_

**Miles you drive per year:** \_\_\_\_\_

**Have you participated in any previous UMTRI studies?** \_\_\_\_\_

If so, how many times? \_\_\_\_\_

**If you were driving on a 3-lane highway, what lane would you typically drive in?**

Left                      Center                      Right

**How many accidents have you been involved in, during the past 5 years?** \_\_\_\_\_

**Have you ever driven a car with a head-up display?** \_\_\_\_\_

**Have you ever used a head-up display in any other context?** \_\_\_\_\_

For Experimenter:

Vision Correction: Yes ( Eye Glass, Hard Contact Lens, Soft Contact Lens), No  
 Titmus Vision: (Landolt Rings)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
T	R	R	L	T	B	L	R	L	B	R	B	T	R
20/200	20/100	20/70	20/50	20/40	20/35	20/30	20/25	20/22	20/20	20/18	20/17	20/15	20/13
1	2	3	4	5	6	7	8	9					
B	L	B	T	T	L	R	L	R					
12	5	26	6	16									



## APPENDIX D - Experiment Protocol

### Before subject arrives

- 1) Get supplies:
  - a) Key to the sim lab
  - b) Forms:
    - i) Consent
    - ii) Biographical
    - iii) Post test evaluation
    - iv) Data collection
    - v) Payment
    - vi) Subject list including tape order
  - c) New videotape
  - d) Floppy disk
  - e) Pen for subject
  - f) Money for subject payment
  - g) Write "sim" on the board
- 2) Setup sim-lab
  - a) Flip experiment signs
  - b) Turn on equipment:
    - i) Low-light camera
    - ii) Psyscope Mac
    - iii) VCR and monitor
    - iv) LCD projector panel - set to VIDEO
    - v) IP projector
    - vi) Sound rack - set VOLUME to 3.5
    - vii) Video rack
    - viii) Main simulator computer and IP computer
    - ix) Insert the new tape into the VCR
  - c) Flat panels:
    - i) Connect flat panels and turn them on
    - ii) Verify appropriate brightness and contrast levels
    - iii) Place cover on flat panels
  - d) Hang windshield - make sure the tape marks are near the ring
  - e) Arrange keypad in the car
    - i) Turn on night light
    - ii) Verify visual of keypad on monitor
  - f) Place and fix cardboard for eye placement and place transparency on projector
  - g) Check the four road tapes and the practice tape
  - h) Insert practice tape into the VCR
  - i) Load Psyscope program: "15 triangles" and check the alignment on the windshield
  - j) Load Psyscope program: "center alignment triangle"
  - k) On IP Mac, quit Labview program, open "Nissan-IP" and move to appropriate location.
  - l) Go wait for the subject to arrive

### Forms and vision test

- 3) Introduce yourself and seat them at the rear table of the sim lab
- 4) Forms



- a) Fill bio form
- b) Fill consent form
- c) Check driver's license
- 5) Vision test
  - a) Test visual acuity (FAR #2)
  - b) **“Can you see in the first diamond that one of the circles is complete but the other three are incomplete? In each diamond, tell me the location of the complete circle - top, bottom, left, or right.”**
  - c) Test peripheral vision (blink from outside in)
  - d) **“Do you see any blinking lights?”**
  - e) Test depth vision (FAR #5)
  - f) **“Can you see in the first diamond that one of the circles is popping out toward you? In each diamond, tell me the location of the circle that is popping out - top, bottom, left, or right.”**
  - g) Color-abnormality (FAR #6)

**“In each circle, there is a number. Starting with Circle A, could you tell me the number?”** {Circle F does not really have a number}

- 6) Ask if subject wants to go to the restroom or get a drink

Seating (height, distance)

- 7) Seating
  - a) Seat the subject
  - b) Adjust seat height so that the subject can see through the tube
  - c) Measure eye height with yardstick
  - d) Measure focal distance with 1m string
  - e) Align visual angle
    - i) Turn on overhead projector
    - ii) Turn off room lights
    - iii) Remove HUD cover
    - iv) Have the subject tell you how to move the circle so that it aligns with the triangle
  - f) Place HUD cover

Tutorial

- 8) Start recording on video rack
- 9) Tutorial
  - a) Play the practice tape
  - b) Go over the tutorial instructions
  - c) **"For the entire experiment, pretend that you are driving. You will not be using any of the foot pedals, but do steer with the road using your left hand."**

- d) "Now I am going to show you the events that you will have to respond to using the key pad on your right. You will have to respond with your middle finger for all the events that occur on the road."

Training Tape Instructions		
Start time	Moving?	Text
0:00:00	Paused	This is the leading car.
0.14.28	Moving	You will be following it at approximately this distance for the entire time.
0.31.04	Paused	You will be asked to respond to three events: the first is passing cars.
0.43.05	Moving	Only respond to cars passing on the left side of the leading car. If you are in the left lane, do not respond to vehicles that pass on the right.
0.56.04	Paused	This is when you respond, when the rear bumper of the passing car is aligned with the rear bumper of the leading car.
1.04.14	Moving	Say CAR when you would respond in this case. {replay until good}
1.16.21	Paused	Here are the other two events to which you will have to respond: Taillights activated by the leading car (brake, left signal or right signal) Yellow diamond road signs on the right side , like this one - when they are aligned with the rear bumper
1.25.20	Moving	Here are some more events. Say CAR, LIGHTS, or SIGN when you see any of the events
When more than one event occurs, respond to each one separately. When two events occur at the same time, press the button twice. Respond as soon as you notice any of the events.		

Road pre-test baseline

10) Road baseline

- a) Mute sound
- b) Place road cover
- c) Insert tape 2
- d) Play over the blank portion
- e) Advance to 2:50:00
- f) Remove road cover
- g) Unmute sound system
- h) Start "road baseline" program
- i) Start videotape when program prompts
- j) Verify timing by listening to beeps
- k) PAUSE the tape at 10:00:00
- l) Mute sound system

HUD pre-test baseline

11) HUD baseline

- a) Pause tape 2 on 10:05:00
- b) Load "HUD baseline" program
- c) Go over the instructions
- d) **"You will see amber triangles appearing on the windshield. Please press the left key with your index finger as soon as you see them. Notice that the left key has a small triangle on it, this should remind you that it corresponds to the warning triangles."**
- e) If there is an assistant, get them ready to remove the cover.
- f) Remove HUD cover
- g) Run the HUD program
- h) Make sure that the video doesn't "sleep" (after 5 minutes) by moving tracking wheel
- i) Place HUD cover when program stops
- j) Place road cover

Full runs \* 4

12) Full Run

- a) Insert tape # (according to predetermined randomized order)
- b) Load "Rtprogram.Tape#" (according to predetermined randomized order)
- c) Go over the blank portion in PLAY mode
- d) Advance to start time
- e) Remove road cover
- f) Unmute sound
- g) Start program
- h) When program prompts, remove HUD cover
- i) When program prompt, play videotape
- j) Listen to driver's responses to verify timing. If necessary - start over or take note.
- k) When program stops (pauses), place HUD cover
- l) Place road cover
- m) Quit program
- n) Mute sound
- o) Verify data collection
- p) Eject tape
- q) (After two runs, turn the lights on for a 6 minutes break)

Road post-test baseline

13) Road baseline

- a) Mute sound
- b) Insert tape 2
- c) Play over the blank portion
- d) Advance to 2:50:00
- e) Remove road cover
- f) Unmute sound system
- g) Start "road baseline" program
- h) Start videotape when program prompts
- i) Verify timing by listening to beeps
- j) PAUSE the tape at 10:00:00
- k) Mute sound system

HUD post-test baseline

- 14) HUD baseline
  - a) Pause tape 2 on 10:05:00
  - b) Load "HUD baseline" program
  - c) Go over the instructions
  - d) "You will now see only triangles appearing on the windshield. Please press the left key with your index finger as soon as you see them."**
  - e) If there is an assistant, get them ready to remove the cover.
  - f) Remove HUD cover
  - g) Run the HUD program
  - h) Make sure that the video doesn't "sleep" (after 5 minutes) by moving tracking wheel
  - i) Place HUD cover when program stops

Forms and payment

- 15) Forms
  - a) Assist subject in getting out of the car
  - b) Seat subject at rear table
  - c) Complete evaluation form
  - d) Go over the form, ask for clarifications and write them in your words
  - e) Ask for additional comments
- 16) Payment
  - a) Choose payment form according to affiliation
  - b) Pay
  - c) Document
- 17) Walk subject to the elevator

Cleanup (simlab, data)

- 18) Cleanup
  - a) Copy data files to floppy
  - b) Close everything
  - c) Shut down
    - i) Close lights
    - ii) Lock the sim-lab
  - d) Make copy of forms and file them
  - e) Copy data from the floppy to a hard disk
- 19) Update the subject data



**APPENDIX E - Post-test Evaluation Form**  
**Subject Evaluation of Head Up Display Study**

Evaluation of the HUD

Do you think that the warning triangles could be useful in drawing your attention while driving?

*Not useful* |-----| *Very useful*

How much did the warning triangles interfere with detecting road events?

*Not interfering* |-----| *Most interfering*

How difficult was it to detect the warning triangles?

*Very easy* |-----| *Very difficult*

Evaluation of the task

How difficult was each of the following tasks? - (Rate 1 [easy] through 6 [difficult])

- Driving only \_\_\_\_\_
- HUD only \_\_\_\_\_
- HUD and Driving \_\_\_\_\_

How was this simulation similar to or different than your real driving?

---

Rank order the priority of events you looked for (1,2,3,4):

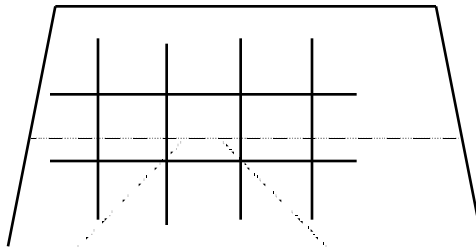
- \_\_\_ Signals presented by the vehicle in front of me
- \_\_\_ Vehicles passing me
- \_\_\_ HUD warning triangles
- \_\_\_ Road signs on the right side of the road

Describe the method that you used to respond to events:

---

Preferred locations of the HUD

Here are 15 locations where triangle warnings could appear on a HUD. Rank the 3 best locations (1,2,3) and the 3 worst locations (13,14,15). Consider both how easy the warnings are to see and the impact on seeing other objects ahead.



Other comments

(Please use other side of this form if necessary)



## APPENDIX F - Additional Images

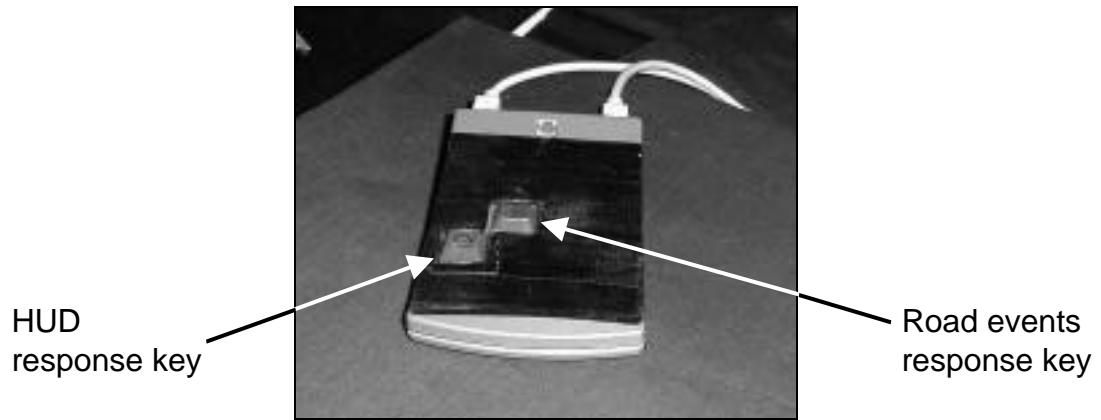


Figure 29. Two-button keypad



Figure 30. Inclinometer with a laser pointer attached





Figure 31. Single triangles appearing on the leading car



Figure 32. Single triangles appearing on the road scene

## APPENDIX G - Supplemental Data

The interaction of HUD response time between trial and vertical location, which is statistically significant, is shown in Figure 34.

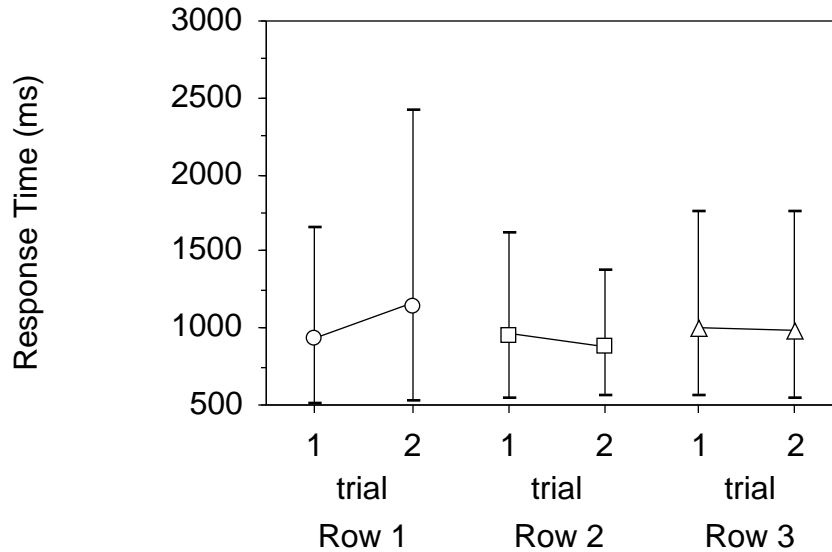


Figure 33. Effect of trial and vertical location on HUD response time

Table 20 shows 8 percentile values of HUD response time for each of the 15 locations in this experiment.

Tables 21 through 25 show the 5 main ANOVA tables as described in Table 5.

Table 20. Percentiles of each location (msec)

Vertical	Horizontal												Vertical percentile				
	A			B			C			D				E			
	young	old	all	young	old	all	young	old	all	young	old	all		young	old	all	
1	95	2677	4188	4248	1107	4370	2323	1047	6145	2912	1104	10000	8805	3753	10000	10000	95
	90	1123	3082	1561	1017	2218	1341	995	2928	1508	987	8197	3775	2078	10000	7294	90
	85	983	1460	1174	901	1676	1125	932	1911	1227	963	6217	1520	1490	7479	4171	85
	75	895	1059	980	815	1119	935	832	1255	1007	871	1676	1047	1070	4160	1813	75
	50	740	886	823	713	863	788	741	968	835	733	948	846	795	1287	1013	50
2	25	648	762	693	592	767	666	650	840	715	633	825	691	694	987	759	25
	10	580	671	601	531	700	573	568	729	616	574	698	597	647	859	672	10
	5	564	622	573	501	636	518	542	695	568	518	650	550	552	794	644	5
	95	1783	4272	2567	1917	6000	3004	1827	2225	2004	1334	2150	1875	1571	2593	2180	95
	90	1248	1857	1547	1286	1581	1412	1487	1497	1508	1061	1354	1263	1145	1753	1559	90
3	85	1052	1517	1290	1070	1394	1237	1331	1206	1254	912	1176	1064	1019	1474	1292	85
	75	860	1255	1020	830	1091	976	993	1125	1065	779	1003	927	936	1235	1047	75
	50	734	887	811	745	855	786	764	938	849	688	842	769	733	1000	875	50
	25	618	743	680	626	745	697	669	778	711	637	765	672	632	857	707	25
	10	570	667	590	565	651	579	585	679	624	601	676	614	574	773	619	10
5	547	616	566	493	577	550	557	625	578	547	638	581	564	741	574	5	
95	3645	10000	10000	2482	2932	2925	1202	4085	2226	1398	6427	3872	1641	2519	2125	2125	95
	90	2466	7723	4312	1781	2006	1860	997	2041	1514	1160	1783	1473	1136	1758	1566	90
	85	1957	4824	2237	1324	1427	1392	941	1640	1267	1022	1513	1254	1001	1476	1294	85
	75	1307	1555	1407	928	1184	1142	871	1264	1006	897	1181	1029	853	1216	1068	75
	50	899	1065	977	763	866	824	742	940	838	751	965	852	732	953	825	50
25	729	823	779	642	780	715	604	813	717	624	810	708	623	793	690	690	25
	10	592	741	644	582	691	612	555	726	582	557	733	589	550	710	602	10
	5	542	637	557	557	661	579	534	715	555	518	706	553	537	678	544	5

Table 21. Anova table of HUD response time

Factor	DF	Sum of Squares	Mean Square	F-Value	P-Value
Age	1	79.51	79.51	15.749	0.0008
Gender	1	3.459	3.459	0.685	0.4176
Age * Gender	1	5.223	5.223	1.035	0.3212
Subject(Group)	20	100.969	5.048		
Horizontal	4	10.133	2.533	6.594	0.0001
Horizontal * Age	4	4.139	1.035	2.693	0.0367
Horizontal * Gender	4	1.402	0.351	0.912	0.4609
Horizontal * Age * Gender	4	0.356	0.089	0.232	0.9198
Horizontal * Subject(Group)	80	30.734	0.384		
Vertical	2	7.029	3.514	3.111	0.0555
Vertical * Age	2	7.996	3.998	3.539	0.0384
Vertical * Gender	2	0.434	0.217	0.192	0.8258
Vertical * Age * Gender	2	0.137	0.068	0.061	0.9413
Vertical * Subject(Group)	40	45.188	1.13		
Run	3	7.897	2.632	6.779	0.0005
Run * Age	3	0.905	0.302	0.777	0.5117
Run * Gender	3	1.667	0.556	1.431	0.2427
Run * Age * Gender	3	1.064	0.355	0.913	0.44
Run * Subject(Group)	60	23.3	0.388		
Trial	1	1.091	1.091	3.497	0.0762
Trial * Age	1	0.177	0.177	0.567	0.46
Trial * Gender	1	0.883	0.883	2.83	0.108
Trial * Age * Gender	1	0.602	0.602	1.93	0.18
Trial * Subject(Group)	20	6.238	0.312		
Horizontal * Vertical	8	27.573	3.447	9.898	0.0001
Horizontal * Vertical * Age	8	5.059	0.632	1.816	0.0776
Horizontal * Vertical * Gender	8	3.291	0.411	1.182	0.3133
Horizontal * Vertical * Age * Gender	8	2.458	0.307	0.882	0.5327
Horizontal * Vertical * Subject(Group)	160	55.713	0.348		
Horizontal * Run	12	3.051	0.254	0.986	0.4631
Horizontal * Run * Age	12	4.219	0.352	1.363	0.1843
Horizontal * Run * Gender	12	1.979	0.165	0.64	0.8073
Horizontal * Run * Age * Gender	12	5.228	0.436	1.689	0.0697
Horizontal * Run * Subject(Group)	240	61.894	0.258		
Vertical * Run	6	1.636	0.273	1.116	0.3572
Vertical * Run * Age	6	2.03	0.338	1.385	0.2262
Vertical * Run * Gender	6	1.055	0.176	0.72	0.6345
Vertical * Run * Age * Gender	6	2.394	0.399	1.633	0.1439
Vertical * Run * Subject(Group)	120	29.322	0.244		
Horizontal * Trial	4	2.748	0.687	2.573	0.0439
Horizontal * Trial * Age	4	1.53	0.383	1.432	0.2309

Horizontal * Trial * Gender	4	1.012	0.253	0.947	0.4412
Horizontal * Trial * Age * Gender	4	0.961	0.24	0.9	0.4681
Horizontal * Trial * Subject(Group)	80	21.366	0.267		
Vertical * Trial	2	10.225	5.113	22.055	0.0001
Vertical * Trial * Age	2	2.083	1.042	4.494	0.0174
Vertical * Trial * Gender	2	0.969	0.484	2.089	0.1371
Vertical * Trial * Age * Gender	2	0.32	0.16	0.69	0.5074
Vertical * Trial * Subject(Group)	40	9.272	0.232		
Run * Trial	3	0.617	0.206	0.857	0.4682
Run * Trial * Age	3	1.882	0.627	2.615	0.0593
Run * Trial * Gender	3	0.325	0.108	0.452	0.717
Run * Trial * Age * Gender	3	0.547	0.182	0.76	0.5209
Run * Trial * Subject(Group)	60	14.395	0.24		
Horizontal * Vertical * Run	24	5.133	0.214	0.887	0.6202
Horizontal * Vertical * Run * Age	24	4.502	0.188	0.778	0.7657
Horizontal * Vertical * Run * Gender	24	7.204	0.3	1.246	0.1964
Horizontal * Vertical * Run * Age * Gender	24	6.195	0.258	1.071	0.3733
Horizontal * Vertical * Run * Subject(Group)	480	115.687	0.241		
Horizontal * Vertical * Trial	8	2.74	0.342	2.152	0.0339
Horizontal * Vertical * Trial * Age	8	1.702	0.213	1.337	0.2287
Horizontal * Vertical * Trial * Gender	8	2.613	0.327	2.053	0.0435
Horizontal * Vertical * Trial * Age * Gender	8	1.808	0.226	1.42	0.1917
Horizontal * Vertical * Trial * Subject(Group)	160	25.461	0.159		
Horizontal * Run * Trial	12	2.099	0.175	0.753	0.6979
Horizontal * Run * Trial * Age	12	2.053	0.171	0.737	0.7144
Horizontal * Run * Trial * Gender	12	1.727	0.144	0.62	0.8246
Horizontal * Run * Trial * Age * Gender	12	2.44	0.203	0.876	0.5721
Horizontal * Run * Trial * Subject(Group)	240	55.71	0.232		
Vertical * Run * Trial	6	0.742	0.124	0.578	0.7472
Vertical * Run * Trial * Age	6	1.765	0.294	1.374	0.2306
Vertical * Run * Trial * Gender	6	1.962	0.327	1.528	0.1748
Vertical * Run * Trial * Age * Gender	6	2.354	0.392	1.833	0.0983
Vertical * Run * Trial * Subject(Group)	120	25.688	0.214		
Horizontal * Vertical * Run * Trial	24	6.271	0.261	1.137	0.2979
Horizontal * Vertical * Run * Trial * Age	24	3.37	0.14	0.611	0.9272
Horizontal * Vertical * Run * Trial * Gender	24	5.487	0.229	0.995	0.4714
Horizontal * Vertical * Run * Trial * Age *gender	24	6.277	0.262	1.138	0.2966
Horizontal * Vertical * Run * Trial * Subject(Group)	480	110.314	0.23		

Table 22. Anova table of HUD response time during the main experiment and the baseline

Factor	DF	Sum of Squares	Mean Square	F-Value	P-Value
Age	1	2.483	2.483	5.129	0.0348
Gender	1	0.032	0.032	0.067	0.7984
Age * Gender	1	1.43	1.43	2.955	0.1011
Subject(Group)	20	9.681	0.484		
Run&base	2	28.502	14.251	116.27	<.0001
Run&base * age	2	1.277	0.639	5.211	0.0097
Run&base * gender	2	0.118	0.059	0.481	0.6216
Run&base * age * gender	2	0.12	0.06	0.489	0.6167
Run&base * Subject(Group)	40	4.902	0.123		
Horizontal	4	0.424	0.106	1.785	0.14
Horizontal * age	4	0.108	0.027	0.455	0.7682
Horizontal * gender	4	0.078	0.019	0.328	0.8583
Horizontal * age * gender	4	0.184	0.046	0.776	0.5438
Horizontal * Subject(Group)	80	4.747	0.059		
Run&base * Horizontal	8	0.542	0.068	1.288	0.2532
Run&base * Horizontal * age	8	0.689	0.086	1.637	0.1181
Run&base * Horizontal * gender	8	0.148	0.018	0.351	0.9442
Run&base * Horizontal * age * gender	8	0.265	0.033	0.63	0.7516
Run&base * Horizontal * Subject(Group)	160	8.417	0.053		

Table 23. Anova table of car response time

Factor	DF	Sum of Squares	Mean Square	F-Value	P-Value
Age	1	0.715	0.715	6.538	0.0188
Gender	1	0.005	0.005	0.046	0.8324
Age * gender	1	0.006	0.006	0.057	0.8133
Subject(Group)	20	2.188	0.109		
Run	3	0.158	0.053	0.803	0.4972
Run * age	3	0.071	0.024	0.36	0.7818
Run * gender	3	0.047	0.016	0.24	0.8683
Run * age * gender	3	0.102	0.034	0.519	0.671

Table 24. Anova table of car response time during the main experiment and the baseline

Factor	DF	Sum of Squares	Mean Square	F-Value	P-Value
Age	1	0.557	0.557	5.565	0.0292
Gender	1	1.46E-04	1.46E-04	0.001	0.9699
Age * gender	1	0.01	0.01	0.1	0.755
Subject(Group)	19	1.902	0.1		
Order	2	0.096	0.048	1.929	0.1593
Order * age	2	0.003	0.001	0.058	0.9434
Order * gender	2	0.01	0.005	0.193	0.8251
Order * age * gender	2	0.019	0.009	0.377	0.6884
Order * Subject(Group)	38	0.947	0.025		

Table 25. Anova table of road detection probability

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Age	1	0.094	0.094	5.064	0.0358
Gender	1	0.002	0.002	0.105	0.7492
Age * Gender	1	0.056	0.056	3.018	0.0977
Subject(Group)	20	0.373	0.019		
Road	3	0.035	0.012	3.395	0.0235
Road * Age	3	0.003	0.001	0.282	0.8383
Road * Gender	3	0.031	0.01	3.039	0.0358
Road * Age * Gender	3	0.012	0.004	1.176	0.3264
Road * Subject(Group)	60	0.205	0.003		