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Driver Response Times to -Windshield, Head-Up Displays for Navigation and Vision Enhancement

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While seated in a vehicle mockup, 12 drivers (6 age 30 or younger, 6 age 65 or older) were simultaneously shown slides of intersections (photographed from the driver's viewpoint) and slides of a navigation display. Drivers indicated whether the two images were for the same or different type of intersection (cross, Y, T, etc.). The navigation information was either presented on an instrument panel (IP) display or superimposed on the road scene, simulating a full-windshield, head-up display (HUD).

The response time data were in reasonable agreement with a previous experiment involving responses to IP displays (mean response time = 1511 ms here, 1629 previously), though the error count was much higher than in the previous experiment. Other findings (plan and aerial views were responded to more rapidly than perspective views, etc.) were also replicated.

Response times to IP displays were considerably longer than those for full-windshield HUDs (1170 ms), as well as for small HUDs (1525 ms from the previous experiment). For HUDs, the color (red, white, or blue) had no significant effect on response time, but those displays that were aligned with the road scene were responded to slightly more rapidly than those that were misaligned (1153 versus 1187 ms).

Given these findings, the authors recommend that further human factors experiments of improved full-windshield HUDs be conducted to establish if engineering development of them should proceed.

17. Key Words
displays, human factors, ergonomics, navigation, route guidance, safety, head-up displays

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Driver Response Times to Full-Windshield, Head-Up Displays for Navigation and Vision Enhancement

umtri HUMAN FACTORS

UMTRI Technical Report 95-29
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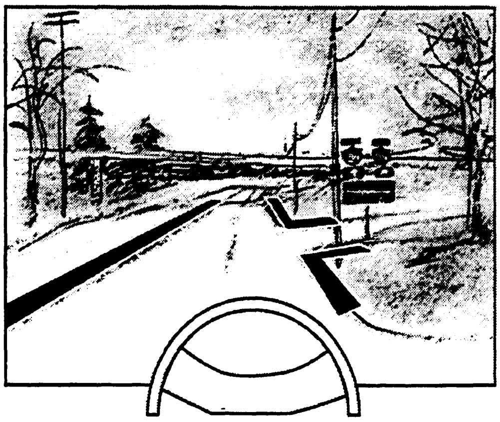
1 ISSUES

1. How well do drivers make decisions using (a) a full-windshield HUD or (b) an instrument panel (IP) display?

2. How much does the color of the HUD graphics (white, red, blue) and their misalignment with the road scene affect driver performance?

3. How repeatable are the results with a previous study using different subjects?



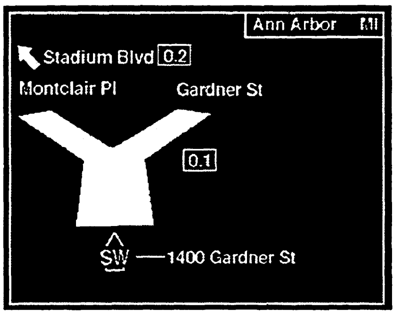
Example: aligned, full-windshield HUD

2 METHOD

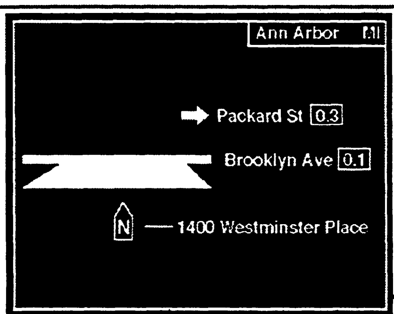
Subjects sat in a car mock-up and compared simultaneously presented slides of road scenes and navigation displays. Subjects keyed in whether the slide images were the "same" or "different".

Instrument Panel Displays

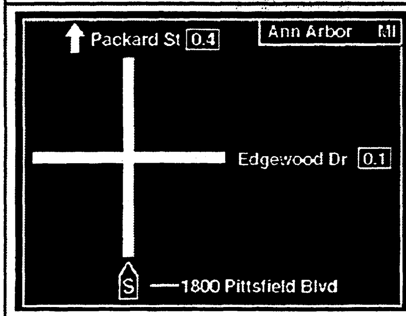
Solid Aerial



Solid Perspective

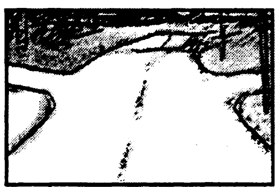


Solid Plan



Responses

"Different" (T & Cross)



"Same" (both Cross)

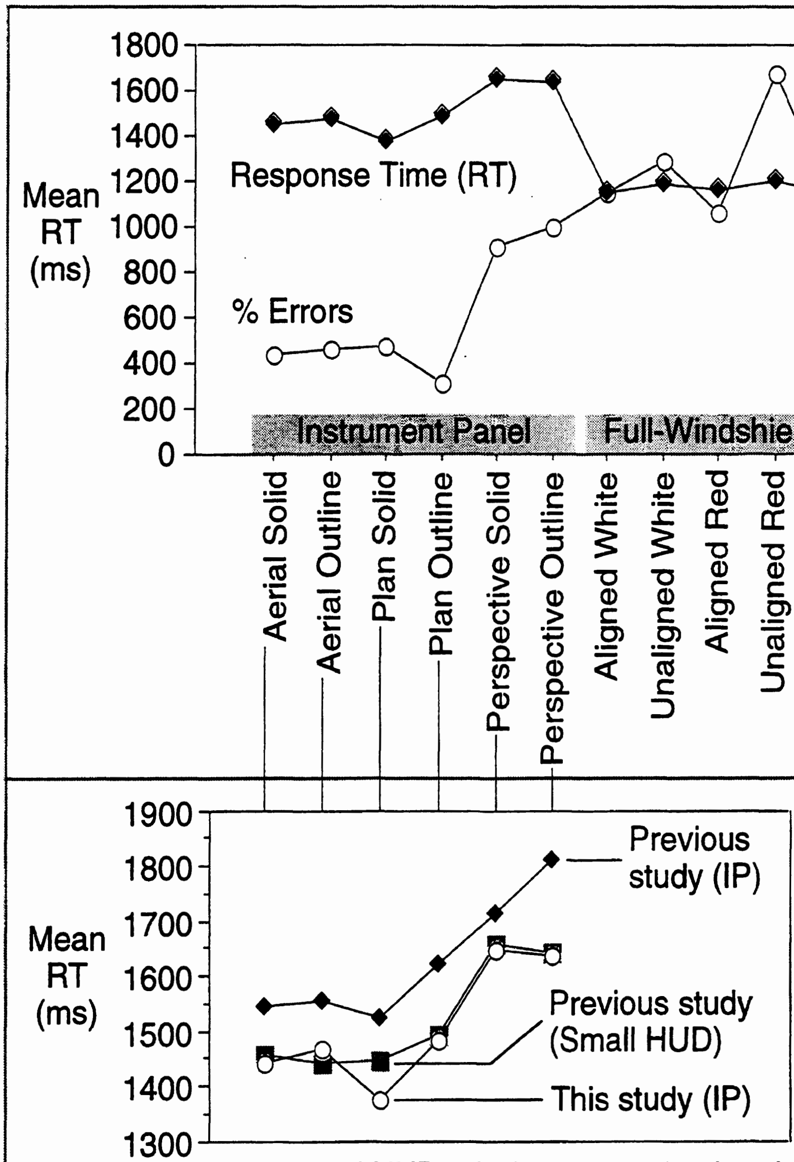
# of Subjects

Age	Men	Women
18 - 30	3	3
65<	3	3

Formats

HUD	Aligned	Unaligned
Blue	x	x
Red	x	x
White	x	x
IP	**Solid**	**Outline**
Aerial	x	x
Persp.	x	x
Plan	x	x

3 RESULTS



The RTs to the IP display for this study were an average of 118 ms less than those in the previous study.

RTs to IP displays from both studies were highly correlated (r=.93).

note: small HUD = IP image on simulated standard size HUD

4 CONCLUSIONS

- The RTs for full-windshield HUD navigation displays were significantly less than those on the IP. The error data favor instrument-panel displays. In a previous study, small HUDs were found to be significanly faster than IP displays.

- Minor flaws in alignment will have minimal impacts on user performance. There was no statistically significant difference due to HUD image color.

- The results of this study were highly correlated to the previous study. The differences between the two studies may be due to a shift in the speed-accuracy tradeoff.

- While full-windshield HUDs are the fastest, efforts to develop such displays should emphasize designs that reduce opportunities for driver errors.

PREFACE

This research was completed as part of the requirements for Industrial and Operations Engineering 499 (Senior Project: Directed Study). The research was conducted by Aaron Steinfeld and was guided by Paul Green. This report is a revision of the original report submitted for that course.

The assistance of Marie Williams in completing this research is gratefully acknowledged.

TABLE OF CONTENTS

INTRODUCTION

Why Examine Full-Windshield, Head-Up Displays?

The purpose of the research was to examine driver performance with a simulated full-windshield, head-up display (HUD) that might be used for navigation. This research was conducted to (1) identify the best possible navigation performance achievable, (2) examine the usability of a particular implementation of a navigation interface, and (3) determine the potential safety benefits of that interface.

While such a device is not practical at the current time, it may be some day. To justify the costly engineering development for a full-windshield HUD, an assessment of the usability benefits (obtained at a much lower cost) is desired. It is important that research be conducted to enhance the application of existing technologies and to identify opportunities for new application development.

To some, the optimal navigation system would be one in which the environment provides fully integrated guidance ("follow the yellow brick road"). Using a HUD to identify route choices in this manner may approximate optimal performance. Optimal performance can serve as a benchmark for weighing the costs and benefits of other less optimal interface designs, not just HUDs or visual displays. For example, if in an experiment, response times to auditory navigation information were within 1 percent of a thought-to-be optimal design, it is unlikely that investment in alternative technologies solely for the purposes of enhanced navigation could be justified on a driver performance basis.

Full-windshield HUDs may provide benefits beyond enhanced navigation performance. By placing navigation information in the driver's field of view, the amount of time the driver is looking away from the road should be reduced. Logically, this should reduce accidents. In addition, full-windshield HUDs are likely to be particularly beneficial to older drivers, the fastest growing segment of the driving population (Jette and Branch, 1992). Advanced technology may help overcome cognitive-motor deficits (Stelmach and Nahom, 1992) and decrements in visual performance (Kosnik, Sekuler, and Kline, 1990; Schieber, 1994) that occur with age.

While there are strong performance arguments for presenting information on HUDs, there are strong performance arguments against HUDs, as well. (See Table 1.) The choice of a HUD for presenting visual information hinges primarily upon the criticality of the information (in terms of frequency or importance) and the cost of a HUD. The authors believe that if well implemented, the arguments for navigation HUDs outweigh the arguments against them, at least in the long term.

Table 1. Arguments for and against HUDs.

Arguments for using a HUD
• Placing frequently looked at information on a HUD (instead of the instrument panel) reduces time looking away from the road. This allows drivers to detect accident provocative situations, thus reducing accidents.
• Critical information requiring a rapid response (collision warning) will be responded to in less time, thus reducing accidents.
• Timely receipt of the information is needed and the information is not available from the environment (in some cases, route guidance).
Arguments against using a HUD
• Placing noncritical information on a HUD blocks the view of the road, making driving more dangerous.
• Placing more information on a HUD complicates the drivers task by providing more information to examine. This is especially problematic if the information is of low priority.
• Information on HUDs may be difficult to read because of low contrast (a current technology constraint) or varying background conditions (changes in the road surface color or luminance).
• HUDs are difficult to use by extremely short or tall people (a current technology limitation of the display envelope, the eye box). Those drivers have relatively fewer problems with instrument panel displays.
• The limited space available on a HUD may not be sufficient to present the desired information (a current technology limitation).
• HUDs are expensive. Instrument panel displays are cheap.

Relevant Research

In this report, the authors do not intend to provide an extensive review of navigation research (see Green, 1992 for a review of U.S. research) or of HUDs (Weintraub and Ensing, 1992; Harrison, 1994). There are, however, a few studies that have a direct bearing on the research reported here.

Shekar, Coyle, Shargal, Kozak, and Hancock (1991) describe two experiments conducted in a driving simulator, each involving 10 subjects. (See also Coyle, Meir, Shekhar, Yang, Caird, Hancock, and Johnson (1991) for an overview of the test facility.) Prior to each experiment, subjects were shown a simple map that they memorized. In the first experiment, subjects saw either text information identifying a blockage ("block on road a") on a HUD, or a simplified map showing the blockage. The HUD map was oriented heading up. The driver's task was to make a right or left turn at an upcoming intersection. The dependent measure was response time, though the initiating and terminating events were unclear. Response times to text were approximately 4.5 seconds, significantly longer than the 1.25 seconds for responding to simplified maps. These results argue strongly for using graphic displays, not text. In the second experiment, the orientation of the map was the primary variable. Response times were approximately 1.25 seconds for heading up, 2.75 seconds for heading down, and 2 seconds for heading left or right.

The experiment described here was prompted by a prior experiment conducted in the same laboratory (Green and Williams, 1992; Williams and Green, 1992). In that experiment there were 12 subjects (6 younger, 6 older). While seated in a vehicle mockup, subjects were shown slides of residential intersections photographed from the driver's viewpoint. Simultaneously, drivers saw slides of a navigation display. Drivers indicated if the two images were for the same or different type of intersection (cross, Y, T, etc.) by pressing buttons. Response times for small head-up displays below the line of sight were less than for instrument panel-mounted displays (1524 versus 1630 ms). In terms of display format, response times for aerial views (similar to that from a low flying airplane) were slightly less than for plan views (1501 versus 1523 ms) and much less than for the driver's perspective view (1706 ms). Benefits of HUDs were larger for older drivers than for younger drivers. Finally, responses to displays where the roads were shown as solid objects were more rapid than to those shown as outlines (1557 versus 1597 ms). While this last difference was small, it was in the expected direction and was statistically significant, showing the sensitivity of this method. Error and preference data supported the results concerning design differences.

Also relevant are several experiments completed after the work described in this report. Flannagan and Harrison (1994) presented drivers with road scenes and simplified plan view maps 4, 9, or 15 degrees below the horizon. Of the 12 scenes (all straight road sections), 6 had pedestrians in them. There were 120 different HUD slides representing 12 variations of 10 basic map displays. After seeing the slide for 30 ms, the driver's task was to verbally identify the final turn direction (left or right) and whether a pedestrian was present in the road scene. There were 24 subjects (12 younger, 12 older). The angle of the HUD from the line of sight had only a small effect on error rate, a result consistent with the instructions in which the HUD task was given primacy. Younger drivers made fewer errors (10 percent versus 20 percent). The HUD angle and driver age significantly affected performance in the pedestrian detection task. This experiment suggests that HUD placement does significantly affect driver performance.

Green, Williams, Hoekstra, George, and Wen (1993) describe two experiments in which drivers used voice guidance, an instrument panel display, or a HUD display (the last two of which showed simplified maps) to follow a 19-turn route. The route included driving in residential areas, business districts, and on expressways, and included a wide range of decision point geometries (typical signalized cross intersections, closely space turns, U-turns, multiple street intersections, streets changing names, etc.). The first experiment, involving pairs of drivers, indicated there were no major problems with any of the three types of interfaces considered.

In the second experiment 43 drivers participated. The results slightly favored the HUD design. With the HUD, drivers made fewer navigation errors (6 for the HUD, 8 for the instrument panel display, 11 for voice guidance). Generally, differences in other driving performance measures were often small, and only sometimes were significant.

Issues

Thus, the literature published both before and after the original research was conducted offers tantalizing suggestions that presenting navigation information on HUDs can be quite beneficial to drivers. The experiment described in this report directly builds upon the research of Green and Williams (1992) and Williams and Green (1992), utilizing the same methods and some of the same stimuli, but in a new way, to examine the benefits of full-windshield HUDs. However, driver performance with and acceptance of full-windshield HUDs has not been examined experimentally.

This research examines the following issues.

1. How well do drivers perform navigation decisions using a full-windshield HUD as compared with a conventional instrument panel (IP) display?
2. How much do the color of the graphics used (white, red, blue) on the HUD and misalignment of the graphics with the real world scene affect driver performance?
3. How repeatable are the results of Green and Williams (1992) across subject samples?

This last question arose because the subjects tested were different from those used by Green and Williams (1992). It was important to avoid confounding design differences with differences between drivers. Replicability was examined by repeating tests of instrument panel display variations (aerial, plan, perspective, solid, and outline) considered in the original research.

TEST PLAN

Overview

The basic protocol was similar to that used by Green and Williams (1992) and Williams and Green (1992). On each trial, a road scene (or a geometric shape in practice trials) slide was shown on a distant retroreflective wall in front of the subject. At the same time, a slide of a navigation system display (or geometric shape) was shown either on the instrument panel or superimposed on the scene (simulating a HUD). The driver's task was to examine the two images and press either a "same" or a "different key". Response times and errors were recorded. After a delay, the projector displayed the next slide.

Test Stimuli

The slides of intersections shown during test blocks were photographed from roughly the driver's eye position in a car. Most were of residential areas in or near Ann Arbor, Michigan, photographed in the fall. For the sake of simplicity, expressway interchanges were not considered. Three examples of five types of intersections (cross, Y, T, T right, and T left) were shown. The intersection slides were the same ones used by Green and Williams (1992) and Williams and Green (1992).

Navigation information was either shown on an instrument panel display or superimposed on the forward scene (simulating a full-windshield HUD). In the instrument panel condition, displays were either of plan, aerial, or perspective views of an intersection, and the image could present the geometry as an outline or solid figure. In the HUD condition, the projection of a second image on top of the road scene simulated a full-windshield display. The navigation information (outlining the intersection) could appear in either white, red, or blue, and was either aligned or misaligned with the road. (In a real system, achieving an unobservable misalignment may be difficult to achieve.) The red and blue colors for the HUD display were produced by placing light filters in front of the shutter for the HUD slide projector. The colors were Lee Filters 115 and 166 (Peacock Blue and Pale Red, respectively). Light levels are listed below in Table 2.

Luminance measurements for various images appear in Table 2. The HUD colors were measured by focusing in the HUD lines with the road scene projector off. The road scene image was measured by projecting a clear slide to determine the maximum luminance level possible in a road scene. The IP level was measured by focusing on the white border line that surrounded the image. The background of the IP display was black. (See Figure 2.)

Table 2. Luminance Measurements and Settings.

	Red	Blue	White	Scene	IP
Variac Setting (to adjust projector lamp voltage)	96	96	68	55	60* (different scale than others)
Luminance (ft-L)	10.94	12	11.98	7.52	1.045

Background (wall focus): .066
* = different variac scale

Figure 1 shows the combinations of slides examined. Figures 2 through 4 provide examples of the instrument panel navigation display slides shown. (The actual displays were in color.) Figures 5 and 6 provide examples of the simulated HUD displays (the gray portions represent where the road would be in the road scene). All slides were highly legible, although one subject reported having difficulty reading in a HUD trial block.

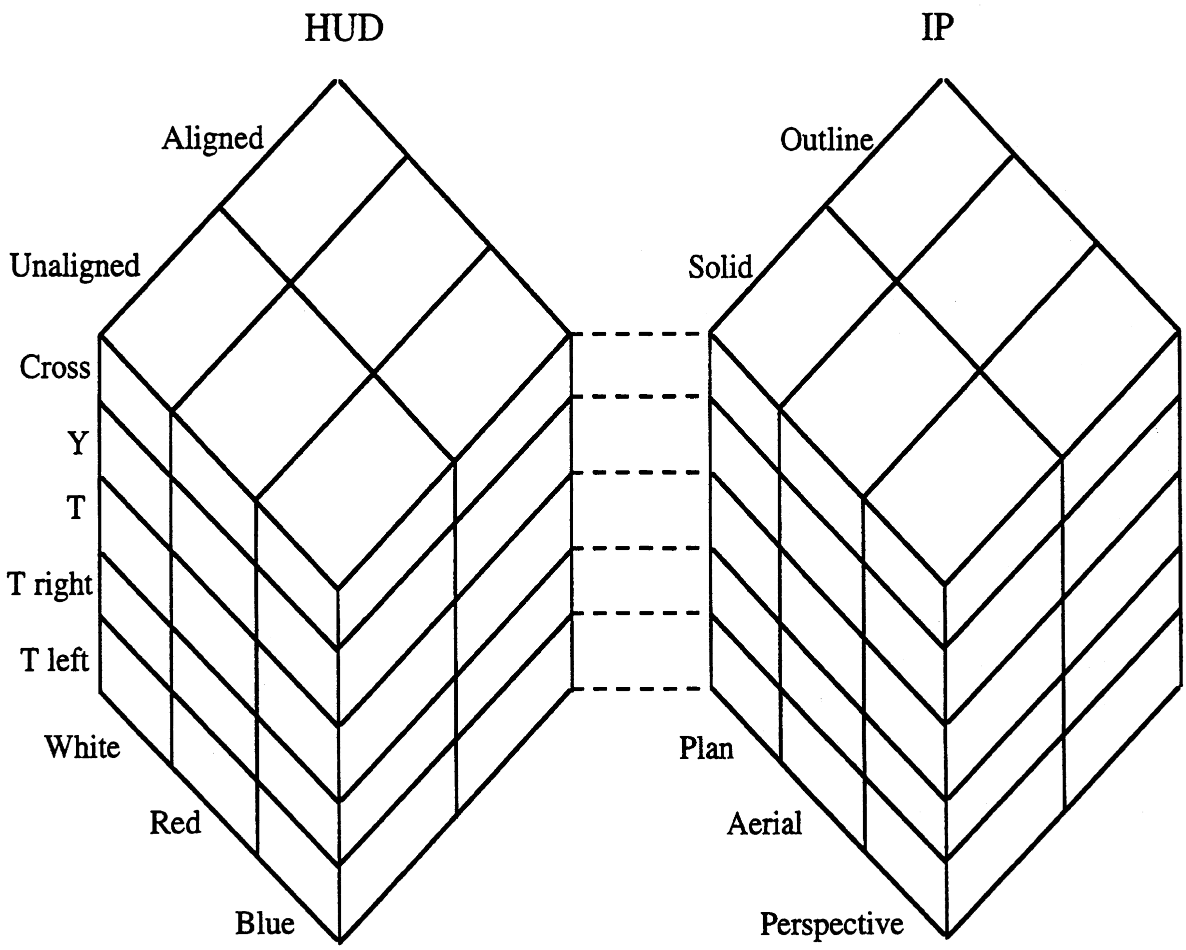


Figure 1. Design of Navigation Experiment.

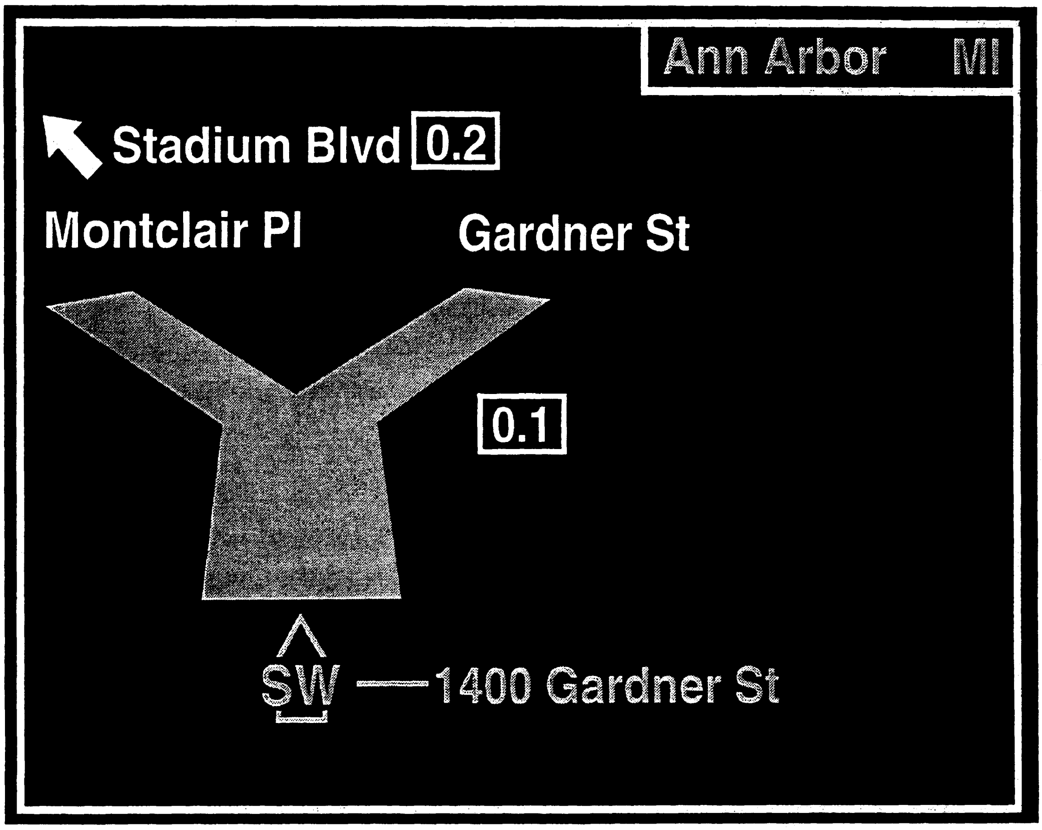


Figure 2. Aerial View of Y Intersection.

Note: The actual displays were in light colors with a black background.

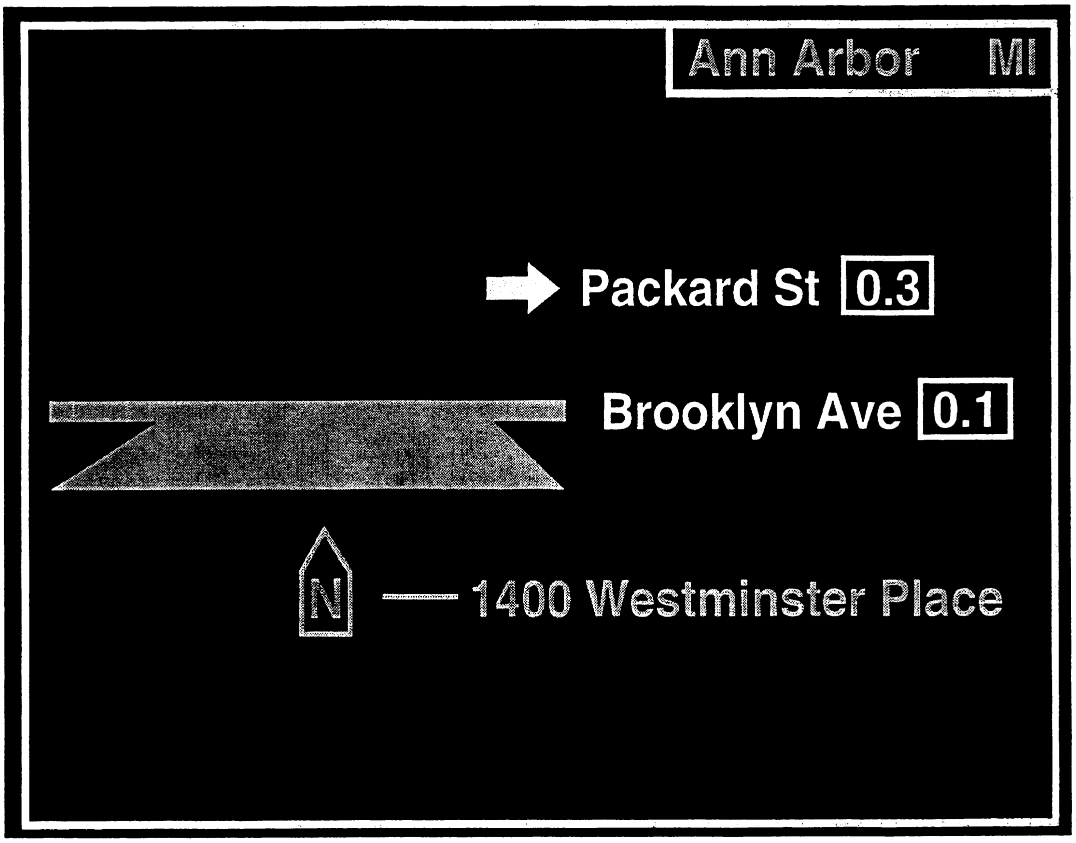


Figure 3. Perspective View of T Intersection.

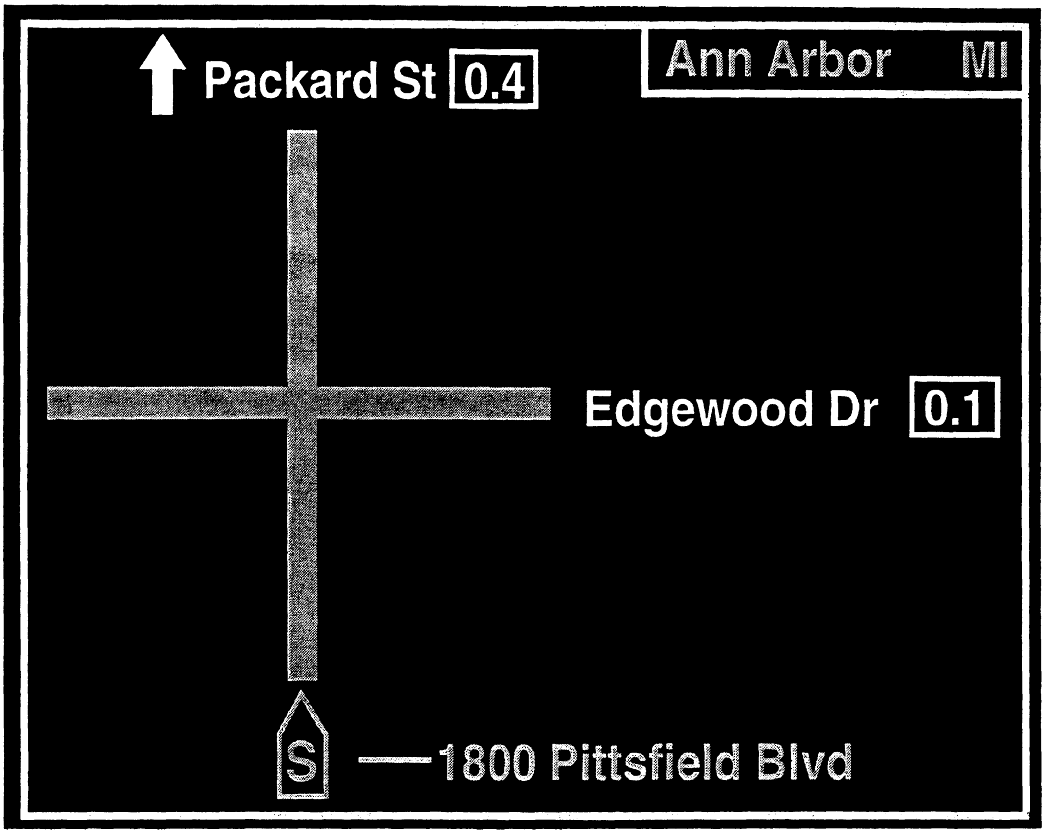


Figure 4. Plan View of Cross Intersection.

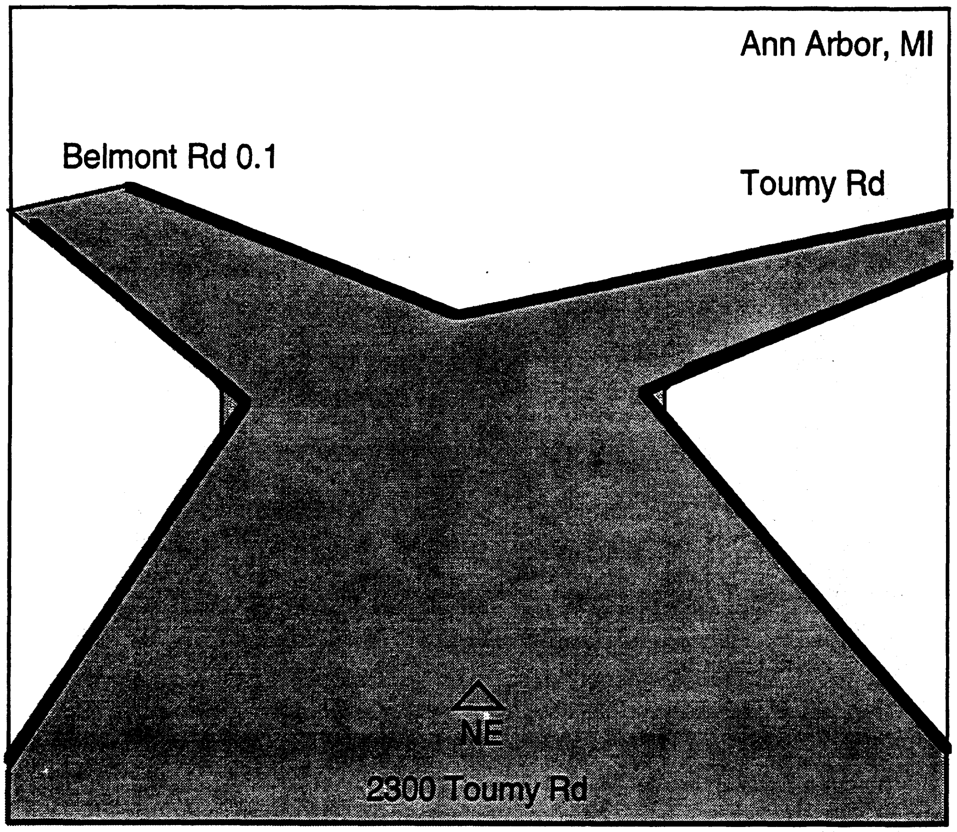


Figure 5. Aligned Full-Windshield, HUD of Y Intersection.

Note: The gray portions represent where the road would be in the road scene.

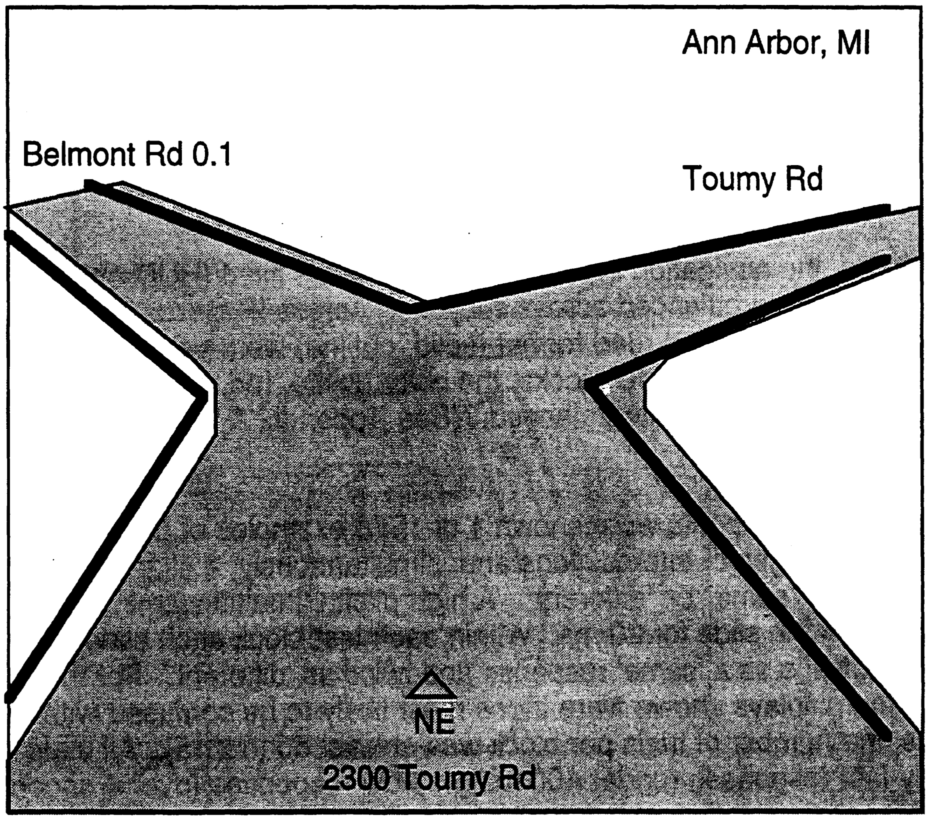


Figure 6. Unaligned Full-Windshield, HUD of Y Intersection.

Test Activities and Their Sequence

After completing a biographical form, answering questions about their use of maps, and having their vision tested, participants were seated in an A-to-B pillar mock-up of a 1985 left-hand drive Chrysler Laser. The participant then adjusted the power seat and the test protocol was explained. On each trial, a road scene (or a geometric shape in practice trials) slide was shown on a retroreflective wall about 7.3 m (20 feet) in front of the subject, essentially optical infinity. Concurrently, a slide of a navigation system display (or geometric shape) appeared either on the instrument panel or superimposed on the scene (simulating a HUD). The display location was fixed for each block. The driver compared the two images and pressed either a "same" or "different" key on the center console armrest using his/her right hand. Response times (to the nearest millisecond) and errors were recorded. After a three-second delay, the projector presented the next randomly-ordered slide.

To facilitate comparison with Green and Williams (1992) and Williams and Green (1992), the total number of practice and test blocks, and the number of trial blocks, were identical to that experiment. Each participant completed 15 blocks of trials (2 practice blocks followed by 6 test blocks, followed by another practice block, followed by 6 more test blocks).

In the practice blocks, participants were shown slides of seven geometric shapes (squares, circles, etc.) on the wall (as in the simulated HUD condition) and on the instrument panel. Each block consisted of 56 trials, with each shape occurring eight times. The probability of "same" and "different" responses was equal, as in the test conditions. This task helped participants learn the same-different response time task without giving them specific practice with the stimuli of interest. This reduced confounding of learning the button-pressing task with learning to use the navigation display. The location of the practice stimuli (HUD or IP) matched the location examined in following test blocks.

In the test blocks, the navigation information location was fixed (HUD or IP) for each 6 block group, but counterbalanced across subjects. Across IP blocks the view (perspective, aerial, plan) and road format (solid, outline) were varied in a counterbalanced order. For HUD blocks, the color (white, red, blue) and alignment (aligned, unaligned) were counterbalanced. (See Appendix A for the order of test blocks for all subjects.)

On each test trial, participants were shown 1 of 15 (3 examples of 5 types) randomly-ordered, life-size images of intersections and, simultaneously, a slide of a navigation display, responding "same" or "different". A high pitch stimulus warning tone preceded the presentation of the slide for 20 ms. Within each test block each slide appeared at least four times, twice as a 'same' response and twice as 'different.' For the different trials, navigation displays shown were those most likely to be confused with the road scene. Thus, the number of trials per block was at least 60 (4 x 15). All trials with exceptionally fast responses (under 400 ms) or slow responses (over 4 seconds) were automatically repeated at the end of each block. Exceptionally fast responses were repeated because they were believed to be trials on which subjects did not fully process the information presented, but rather "guessed" at the response as soon as an image appeared. Some of these trials were instances where the subject may have inadvertently pressed a response key. The long responses represented situations where, for a variety of reasons, the subject may have not understood the stimulus (and may have stopped to ask a question), a very different situation from a typical response trial. The maximum allowable response time was five seconds. If a subject did not respond within this time, the trial was also repeated. By removing these outliers from the data set, the analysis was based on a more representative set of responses. Consequently, each block contained an equal number (60) of correct responses with reasonable times (no missing data). (See Appendix B for the order of slides in each carousel.)

Error trials were also repeated so there would be an equal number of correct responses to facilitate the use of ANOVA. When an error occurred, a low pitch tone was presented for 300 ms, and there was an additional 200 ms delay added to the intertrial interval (normally 2800 ms) to allow the subject to recover from the error.

After completing the response time portion of the experiment, participants rated the 12 designs from best to worst. Testing sessions were about two hours long per person.

Test Equipment and Materials

The overall arrangement of equipment is shown in Figure 7.

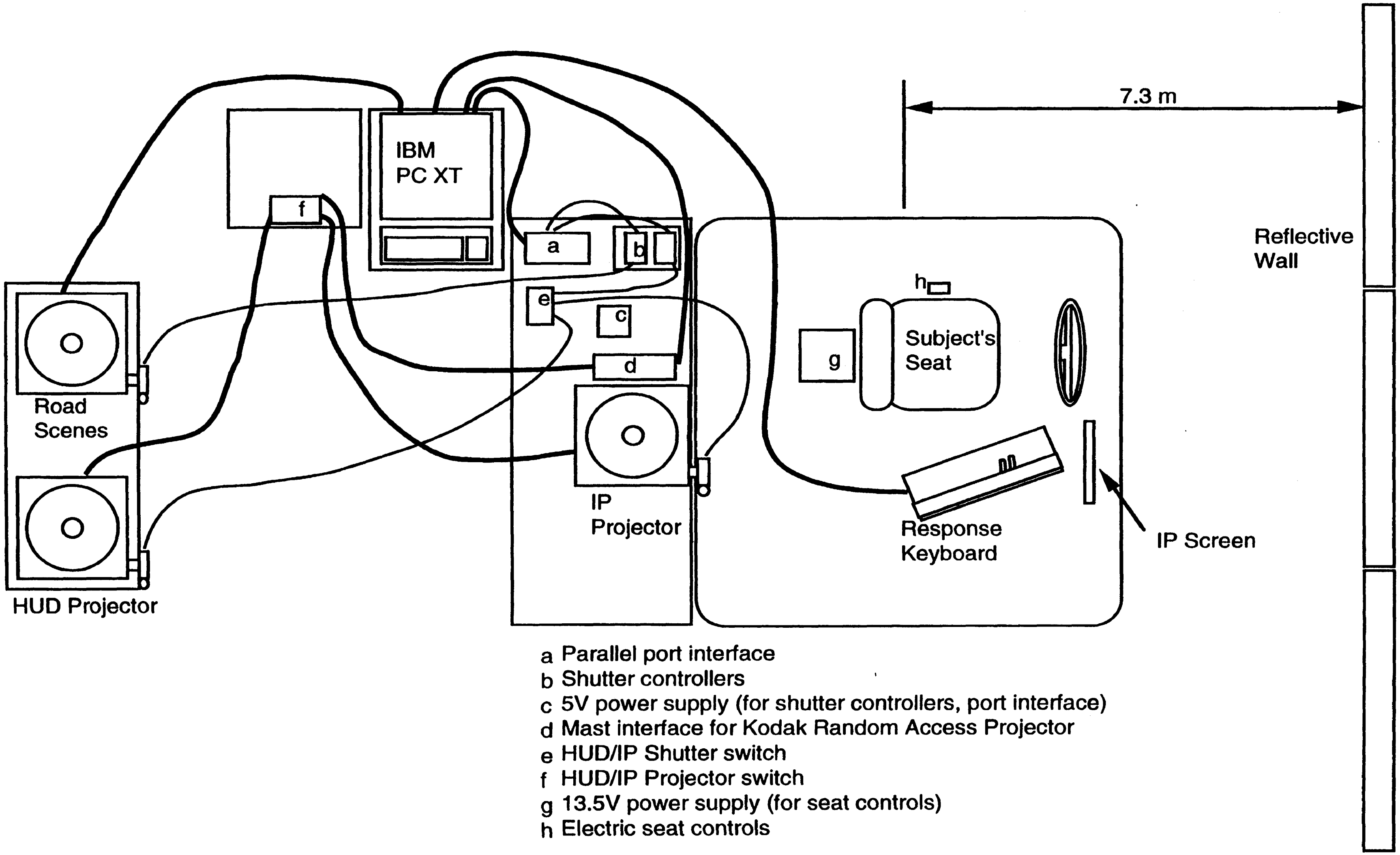


Figure 7. Plan view of laboratory set-up.

Three random-access slide projectors (one Mast System 2, two Kodak Ektagraphic RA-960s), fitted with Lafayette external shutters and custom controllers, presented the slides. An IBM XT computer fitted with a custom interface/timing board controlled the projectors. Input from participants was obtained from a custom keyboard with two piano-like keys mounted above microswitches. The keyboard was within easy reach on the center console.

Other miscellaneous equipment used included a Titmus model OV-7M Vision Tester and a Photo Research model PR-1980A-CD digital Spot Photometer which was used to measure display lighting levels.

Forms used included a consent form (see Appendix C), a biographical form (see Appendix D) and a tabular form for recording driver's display preference.

Test Participants

Twelve licensed drivers participated, 6 younger (18-30) and 6 older (65 or above). Within each age bracket there were three men and three women. Participants were recruited from personal contacts and lists from previous, unrelated UMTRI studies. All were paid $15 for their participation.

The mean age was 21 for the younger subjects and 73 for the older subjects. Corrected visual acuity for the younger subjects ranged from 20/13 to 20/25. For the older subjects it ranged from 20/15 to 20/70. Participants reported driving 500 to 30,000 miles per year with a mean of 9,200 miles. Four of the older subjects reported using an in-vehicle traffic information or navigation system during previous, unrelated experiments. No subjects had driven an automobile with a HUD. When asked to list the number of times they used a map in the past six months, the range was 0 to 9 or more, with an average of about 4.1.

RESULTS

The dependent measures in this experiment were response time and error rate, as well as preference rankings for the alternative displays. Prior to the analysis of each variable, no steps were taken to filter the data set. Analysis of the error data is described first, followed by the response time data and the preferences.

Errors

As keys were pressed, responses were coded by the software as (a) within or outside of the time deadlines (both too fast and too slow), and (b) if they were correct or not. Table 3 shows the coding scheme.

Table 3. Response Types and Codes.

	Correct Choice	Wrong Choice
Within Time Allowed	1 (used for *RT* analysis)	2 (used for *Error* analysis)
Too Fast	3	4
Too Slow	5	6
No Response	7	

Table 4 shows the number of responses of each type. Responses that were too fast were much more likely to be correct than incorrect. This suggests the lower minimum response time deadline may be appropriate in future studies (e.g., 300 ms instead of 400 ms). Likewise, for slow responses the same is true, with a higher deadline being desired (5000 ms instead of 4000 ms).

Table 4. Frequency and Number of Each Response Type for All Trials

	Correct Choice		Wrong Choice	
	Number	Percent	Number	Percent
Within Time Allowed	8640	85.89	1206	11.99
Too Fast	12	0.12	9	0.09
Too Slow	133	1.32	48	0.48
No Response	11	0.11		

The focus of the error analysis was on incorrect responses within the time deadlines, 11.99 percent of all responses, 12.25 percent of responses within the time allowed. These error rates are larger than those typically reported for response time experiments. Other responses (except for correct responses) were too infrequent for analysis.

Table 5 shows the total error counts (out of 720 responses) and percentages for each subject, as well as totals by sex and age. The difference for sex was less pronounced than that for age, with women (56.9 vs. 43.1%) and older subjects (57.4 vs. 42.6 %) accounting for slightly more errors. In terms of individual differences, subjects 1 and 11 had particularly high error rates (389 and 318, respectively, representing 59% of all error responses). Inidividually, the other subjects contributed 10% or less of the total errors, with most being under 5 percent. The first subject had commented upon arrival that she was rather tired from preparing for final exams (she participated in the study within a day of her last exam). Also, she adopted a speed emphasis strategy. (Her mean response time was the second fastest). Subject 11 was an older male who had particular difficulty with the HUD method of display (20 to 50 extra trials per block). He had some difficulty in the first block of the IP condition, but made only a few errors per block for the last 5 blocks.

Table 5. Number and Percentage of Errors per Subject.

	Sex					
Age	Men		Women		Mean	
	Errors	Percent	Errors	Percent	Errors	Percent
Young	29 14 24	4.0 1.9 3.3	389 33 25	54.0 4.6 3.5		
Mean	22	3.1	149	20.7	86	11.9
Old	98 37 318	13.6 5.1 44.2	30 83 126	4.2 11.5 17.5		
Mean	151	21.0	80	11.1	115	16.0
Grand mean	87	12.1	115	16.0	101	14.0

Table 6 shows the sorted number and percentage of all errors for all display formats. The most error-free format was Plan Outline. Over two-thirds of the errors were committed during the HUD trials and none of the HUD trials produced fewer errors than any of the IP trials. There were fewer errors for aligned HUD images than for unaligned (357 vs. 463 errors), with color having only a small effect. For the IP designs, error rates were always lower for solid than outline formats, with performance for the perspective view being worse than that for the plan and aerial views.

Table 6. Errors for Each Display Format (In Order of Increasing Errors).

Code Number	Location	Format	Errors	Percent
4	IP	Plan Outline	34	2.8
1	IP	Aerial Solid	47	3.9
2	IP	Aerial Outline	49	4.1
3	IP	Plan Solid	51	4.2
5	IP	Perspective Solid	98	8.1
6	IP	Perspective Outline	107	8.9
		IP Total	386	32.0
9	HUD	Aligned Red	113	9.4
11	HUD	Aligned Blue	121	10.0
7	HUD	Aligned White	123	10.2
8	HUD	Unaligned White	138	11.4
12	HUD	Unaligned Blue	145	12.0
10	HUD	Unaligned Red	180	14.9
		HUD Total	820	68.0

Even though subjects were given moderate amounts of practice, learning effects were still quite apparent in the error data (as shown in Figure 8), suggesting that additional practice may be desired, or that the practice task should more closely resemble the test task. The increase from block 6 to 7 represents the transition to a new design (HUD to IP or vice versa).

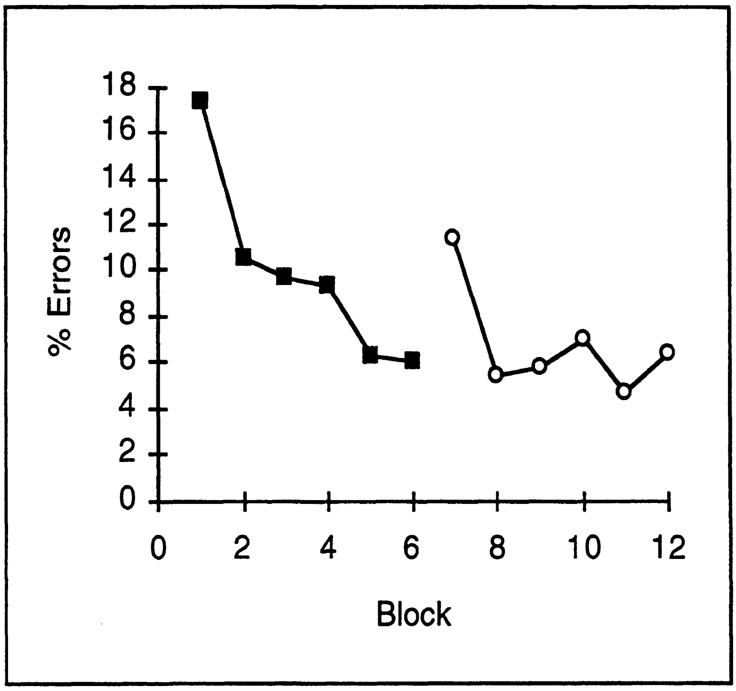


Figure 8. Number of Errors by Block.

Response Time

Response times were examined in steps for computational ease. One way ANOVAs revealed that both the effects of same versus different responses ($F(1,8638)=9.56$, $p=.002$) and test blocks ($F11,8628)=64.64$, $p<.0001$) were significant. The mean response time for same responses was about 50 ms less than that for different responses (1317 versus 1363 ms), a finding consistent with the literature. Figure 9 shows the relationship between test blocks and response time. The elevated times in blocks 5 and 6 reflect difficulties some of the older drivers had with particular displays. The drop from block 6 to 7 may in part be a combination of counterbalancing constraints and improved performance after a rest break. (Half the subjects responded to HUD slides for the first six blocks and IP slides for the last six. The other half of subjects had the two conditions reversed.)

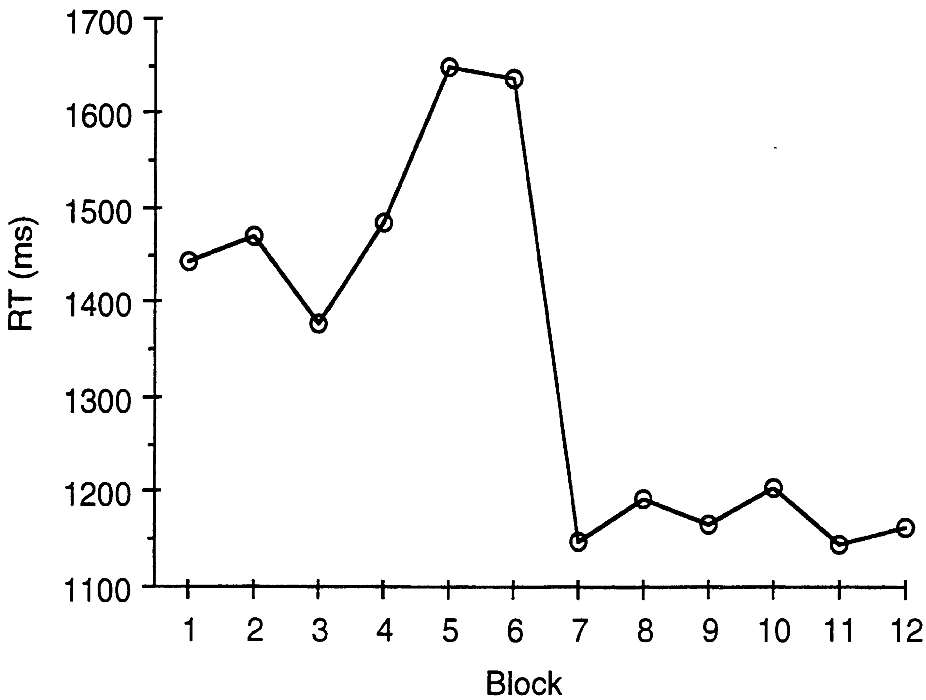


Figure 9. Response Time by Test Block.

The primary analysis was a two-way ANOVA of the pooled subject and interface design differences. Both the effects of subjects ($p<.0001$) and interface design ($p<.0001$) were highly significant. Also significant was the interaction of these two factors ($p<.0001$). Each of the two main effects (subjects, interface design) was partitioned for further analysis.

In terms of subject variables, the factors in the model were Age, Sex, Age*Sex, and Subjects (nested within Age and Sex). All were highly significant ($p<.0001$). Table 7 shows the mean response time for each participant. The mean response time was approximately 970 ms for both younger men and women. However, for older subjects the mean response time was 1826 ms for men and only 1597 ms for women, a 229 ms difference. This is less than the 742 ms difference due to age, amounting to a 76% increase in response time for older drivers.

Table 7. Mean Response Times (ms) by Participant.

	Sex		
Age	Men	Women	Mean
Young	1032 1207 678	831 1047 1024	
Mean	972	967	970
Old	2155 1537 1787	1423 1938 1431	
Mean	1826	1597	1712
Grand mean	1399	1282	1341

In terms of interface differences, responses to HUD displays were significantly faster than those to instrument panel displays ($p<.0001$). IP displays had mean times of 1511 ms versus 1170 ms for HUDs, a 341 ms difference. If the IP display is considered the baseline, employing a HUD should result in a 22% improvement in performance. As shown in Figure 10, the improvements were even larger for older drivers, especially men.

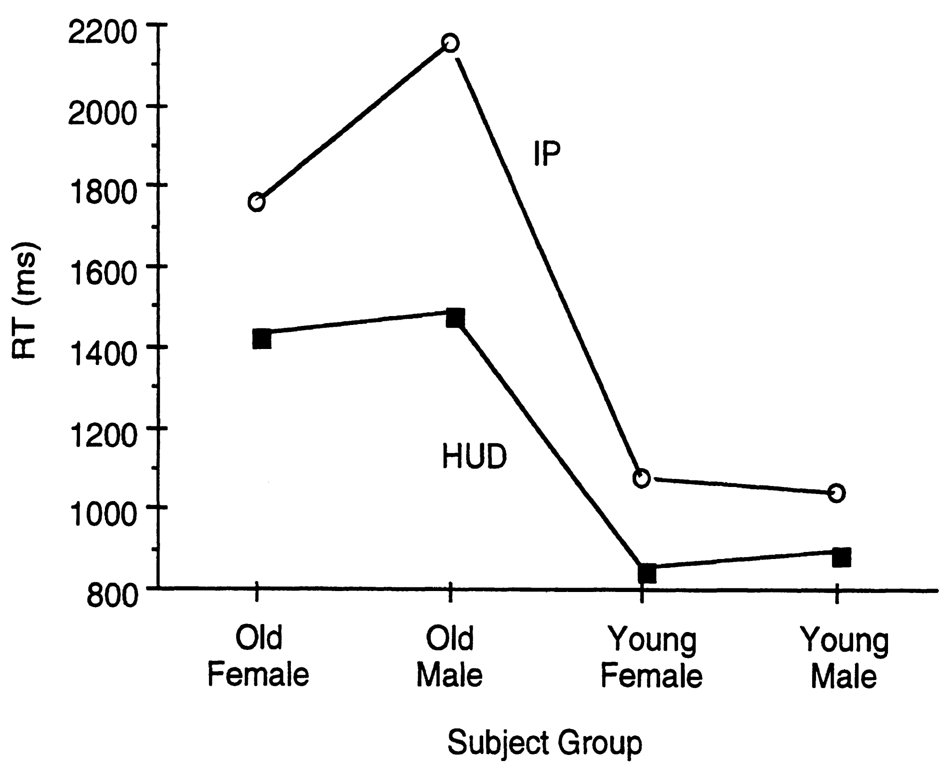


Figure 10. Interaction between Age, Sex, and Display Interface Type.

As shown in Figure 11, response times for HUDs were less than those for instrument panel displays for all of the slide combinations (15 intersections * 2 (one same response, one different response)), though there were two instances where the differences were small. For HUD combination 6, one of the "different" responses (when a cross intersection was shown) came close to matching the scene (of a T-right) because of a driveway on the left. For HUD combination 23, the displayed Y intersection closely resembled a T intersection (one of the "different" responses). Both of these combinations exhibited high error rates, as well.

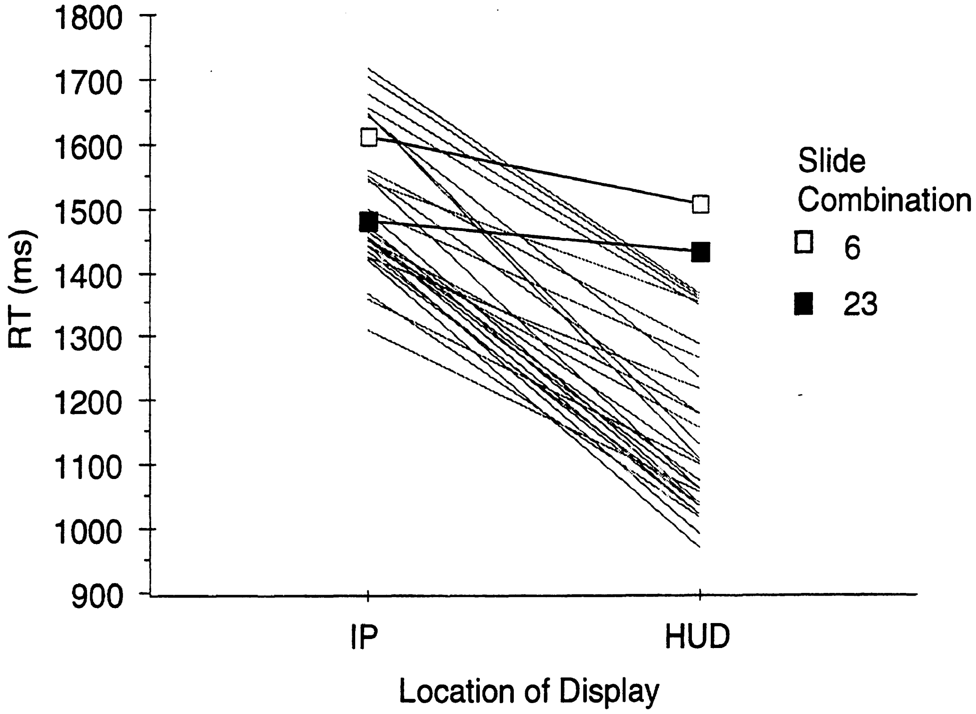


Figure 11. Response Times for Each Slide as a Function of Display Location.

There were other interface differences within the basic IP-HUD comparison. An ANOVA of the various IP designs revealed the differences among views (plan =1432 ms, perspective=1644 ms, aerial=1457 ms) were significant ($p<.0001$). Differences due to fill (solid versus outline, 1491 versus 1531 ms) and the fill by view interaction were marginal ($p=.06$). Figure 12 shows these relationships.

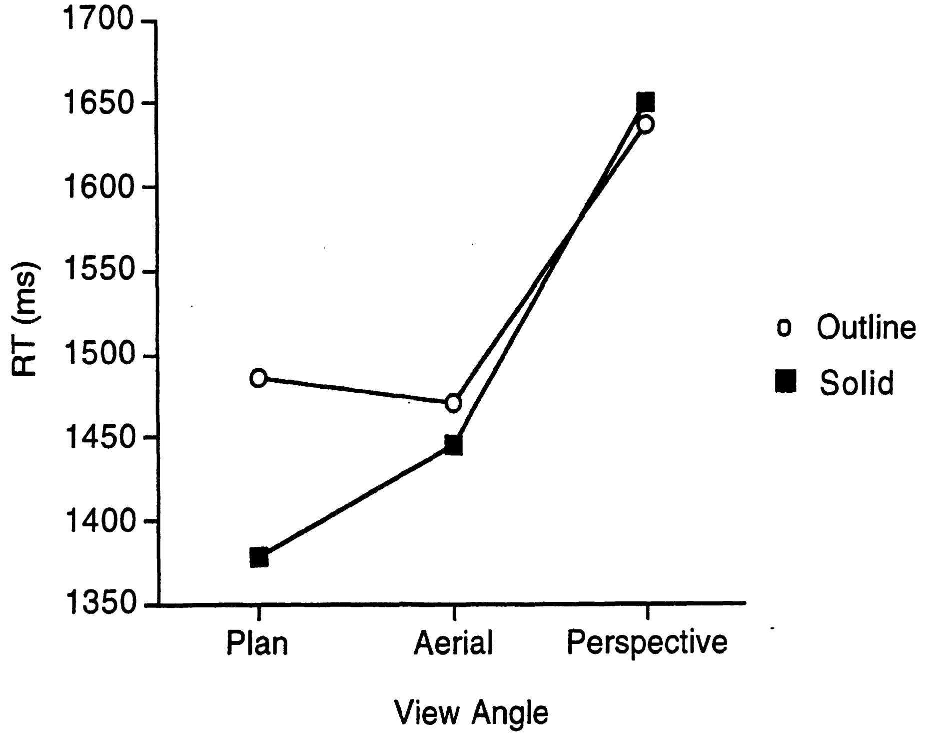


Figure 12. Mean Response Time for Instrument Panel Displays.

Figure 13 depicts the results for HUDs. Whether the HUD image was aligned with the forward scene or not had a marginal effect on performance (p=.06), with aligned displays being just over 30 ms faster (1153 versus 1187 ms). There was no difference due to the color of the HUD image (p=.38, blue=1155 ms, white=1170 ms, red=1186 ms) and no interaction between color and alignment.

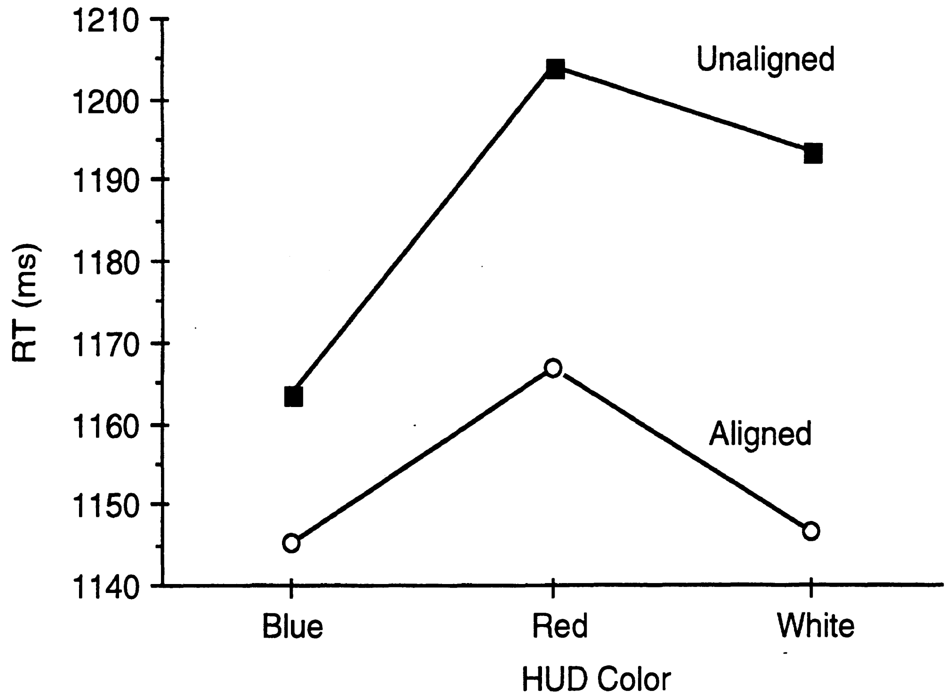


Figure 13. Differences in Response Times to HUDs due to Light Color and Alignment.

Comparison with Previous Research

A key aspect of this experiment was a check of the replicability of a previous experiment (Green and Williams, 1992; Williams and Green, 1992). The numbers of trials, slides, and the instrument panel condition were the same as those used in the previous experiment. The subjects and navigation stimuli (but not the road scenes) used in the HUD trials were different.

The error counts for the the previous experiment and this one are compared in Table 8. There were about 100 more errors made in this study for the IP. An interesting point of observation is that the small HUD from the previous experiment produced slightly fewer errors than the IP. However, in the current study, the wide field-of-view HUD produced a considerable increase in errors.

Table 8. Error Count by Display Type for Each Study

	Experiment	
Location	This experiment	Williams & Green
IP	386	267
HUD	820 (large HUD)	258 (small HUD)

Figure 14 shows the number of errors made by each subject after they have been sorted in ascending order. Note that the two subjects previously mentioned who had high error rates (subject 1 and 11), do not have counterparts in the previous study. In retrospect, these subjects should probably have been replaced prior to conducting detailed analysis.

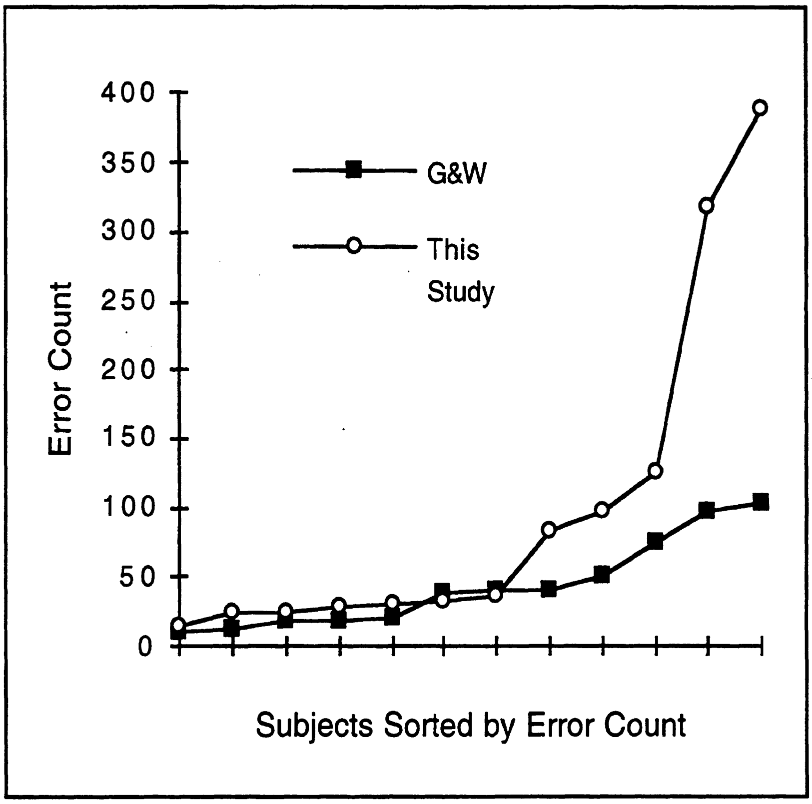


Figure 14. Error Production of Subjects

Table 9 displays the impact of these two subjects on the mean subject error counts. In each age group of the two studies, the most error producing subject was removed from the group. Note that the error results from this study are more similar to the previous study after this analysis filter has been used.

Table 9. Mean Errors by Age for Each Study

	This experiment	This study without worst	Williams & Green	Williams & Green without worst
Young	85.7	25.0	20.2	16.2
Old	115.3	74.8	67.3	60.2

The mean response times for correct responses for each display format from this and the previous experiment are shown in Table 10. Although subjects in both experiments were matched in age and sex, shown the same slides, given the same amount of practice, and used the same equipment, subjects in this experiment tended to be faster (by 118 ms on average). However, across the two data sets, the results for each design were highly correlated (r=.93). (See Figure 15.) Taking this into account, the full windshield HUD examined in this experiment still had response times several hundred milliseconds faster than a conventional HUD.

Table 10. Mean Response Times for Each Format (ms)

Number	Format	Mean (this experiment)	Mean for IP (Williams & Green)	Mean for Small HUD (Williams & Green)
1	Aerial Solid	1444 (IP)	1547	1459
2	Aerial Outline	1470 (IP)	1557	1443
3	Plan Solid	1379 (IP)	1524	1447
4	Plan Outline	1486 (IP)	1623	1497
5	Perspective Solid	1651 (IP)	1714	1657
6	Perspective Outline	1638 (IP)	1811	1646
	Mean	1511 (IP)	1629	1525
7	Aligned White	1147 (HUD)*		
8	Unaligned White	1193 (HUD)		
9	Aligned Red	1167 (HUD)		
10	Unaligned Red	1204 (HUD)		
11	Aligned Blue	1145 (HUD)		
12	Unaligned Blue	1164 (HUD)		
	Mean	1170 (HUD)		

* Note: For this experiment, the HUD data are for a full-windshield HUD.

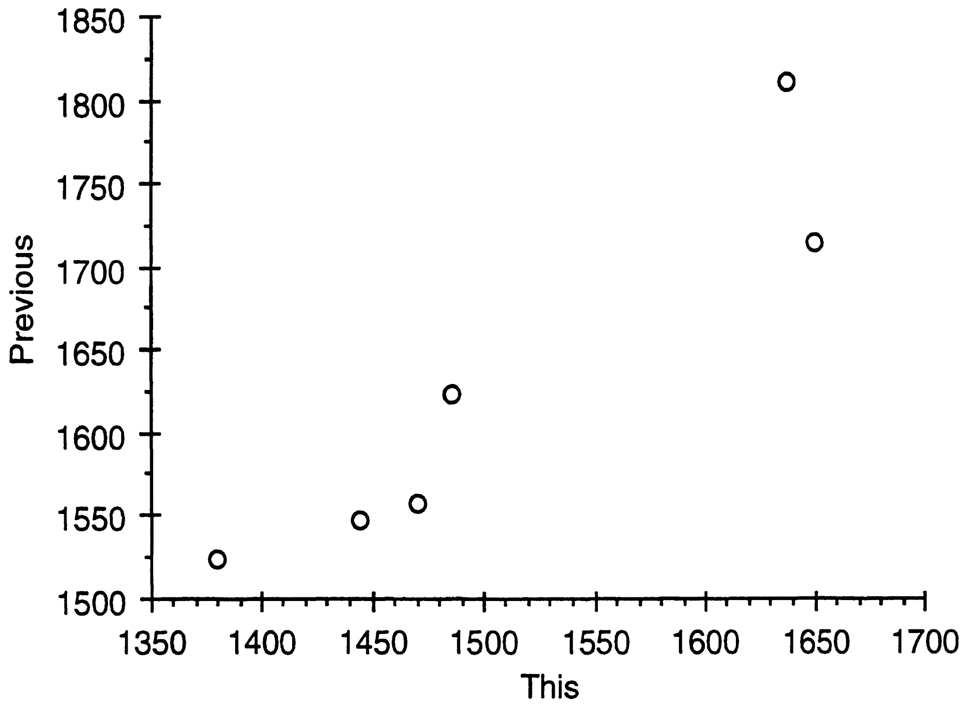


Figure 15. Correlation of Means from this Experiment with the previous Experiment.

Rankings

Table 11 shows the preference rankings of the formats collected at the conclusion of the testing, along with the error and response time ranks. Two of the subjects were not able to provide rankings as they thought the displays were all quite similar. Hence, the rankings are based on 10 subjects. Subjects generally preferred the easy to use designs (as assessed by response time), such as the aligned HUD, plan and aerial solid views on the IP. The more difficult to use designs were less preferred. However, the pattern did not strictly follow the response time data. The correlations were not high (preference-error r=0.39, preference-time r=0.34, time-error r=-0.64). Only the correlation between time and errors was significant (p<.03).

Table 11. Subjective Rankings (Ordered by Increasing Response Time).

Type	Mean Rank	Preference Rank	Location	Error Rank	Time Rank
Aligned Blue	4.0	1	HUD	8	1
Aligned White	6.0	7	HUD	9	2
Unaligned Blue	7.7	8	HUD	11	3
Aligned Red	4.7	3	HUD	7	4
Unaligned White	8.9	11	HUD	10	5
Unaligned Red	8.1	10	HUD	12	6
Plan Solid	4.3	2	IP	4	7
Aerial Solid	5.7	5	IP	2	8
Aerial Outline	5.2	4	IP	3	9
Plan Outline	5.9	6	IP	1	10
Perspective Outline	9.3	12	IP	6	11
Perspective Solid	7.8	9	IP	5	12

Note: For preference ranks, 1 = best, 12= worst.

CONCLUSIONS

1. How repeatable are the results of Green and Williams (1992) across subject samples?

In both experiments the same instrument panel navigation slides and road scenes were used, with subjects receiving the same number of practice and test trials under similar lighting conditions. Subjects in both samples had the same age and gender distributions. Hence, the two sets of data were quite comparable. In this experiment the mean response time to IP displays was 1511 ms, 118 ms less than the 1629 ms reported by Green and Williams (1992). However, the correlation of the mean response times for the 6 display variations was 0.93, highly significant. The rank orders of the 6 display types in the two studies (based on time) were identical.

This 118 ms difference is approximately 8 percent and may be the limit of between-experiment measurement error. A more likely explanation is a difference in the speed-accuracy tradeoff. In this experiment, while subjects responded more quickly, they made more errors (386 responding to instrument panel slides here, 267 in Green and Williams, 1992). Had the speed-accuracy tradeoff in the two experiments been the same, it is likely the differences in response time would have been much smaller. Control of the speed-accuracy tradeoffs across experiments with different groups of subjects is extremely difficult to achieve.

It therefore is the opinion of the authors that the two experiments agree quite well.

2. How well do drivers perform navigation decisions using a full-windshield HUD as compared with a conventional instrument panel (IP) display?

The mean response time for full-windshield HUDs was 1170 ms in this experiment versus 1525 ms for the small HUD in a previous experiment (Williams and Green, 1992), and 1511 ms for the IP display in this experiment (1629 ms previously). Thus, responses to the full-windshield HUD were 341 ms faster than the IP display, a 22.6% difference. This is a difference of practical importance. Between-display differences were more pronounced for older drivers.

However, the error data favor instrument-panel displays. In this experiment there were 386 errors (8.9 percent error rate) in responding to IP displays in the first 60 trials per block, and 820 errors (19.0 percent error rate) for HUDs. In both experiments, there were problems with a few older drivers understanding how to respond to the displays, an experimental artifact. Thus, while the error data are less dependable than the response time data, a factor of 2 difference in error rates cannot be ignored.

3. How much do the color of the graphics used (white, red, blue) on the HUD and misalignment of the graphics with the real world scene affect driver performance?

Slight misalignments of the full-windshield HUD image with the road scene increased response times from 1152 to 1187 ms, a 35 ms difference. (It was statistically significant.) This suggests that minor flaws in implementation will have minimal impacts on user performance (though potential buyers may complain about misalignment). There was no statistically significant difference due to HUD image color (blue 1155 ms, white 1170 ms, red 1186 ms), giving engineers the flexibility of choosing among a variety of display technologies to present the full-windshield image.

However, observation of driver responses and comments suggest improvements to the HUD image (use of thicker lines, filling in of guidance arrows) may be beneficial and should be explored in further research.

4. Which display is best?

For instrument-panel displays, both experiments led to the same conclusion. Drivers do about equally as well with aerial and plan view displays, and considerably worse with perspective displays. Aerial and plan views were preferred by subjects. For instrument panel displays, showing the road graphic as a solid figure and not an outline is preferred. Thus, if a guidance display is located on the instrument panel, the image should present either a plan or an aerial view, and the roads should be shown as solid figures.

When the image is presented on a small HUD, performance improves (response times decrease, typically by values approaching 10%, a value of engineering significance). When full-windshield HUDs were provided, times decreased by at least 20% over the baseline instrument panel displays, though error rates (a less dependable measure) increased by a factor of 2. In terms of subject preferences, an implementation of the full-windshield HUD was the most preferred display.

5. Should navigation displays be presented on HUDs?

The evidence suggests that response times to HUD-based navigation displays will be significantly less than for similar displays mounted on the instrument panel. When the entire windshield was used for the HUD, even greater response time benefits were achieved. Recent on-the-road experiments with small HUDs have shown that drivers make fewer navigation errors with HUDs than with IP-based navigation displays, though the differences were not large for well designed navigation interfaces (Green, Williams, Hoekstra, George, and Wen, 1993; Green, Hoekstra, and Williams, 1993). The decision to implement HUDs for navigation will depend on the tradeoff of the performance benefits for HUDs with their considerably greater cost. This decision will also depend upon the customer demographics (HUDs are more beneficial for older drivers) and the extent to which technological innovation is important to the customer.

6. Should further work be done on full-windshield HUDs?

The findings of this experiment do not provide resounding support for full-windshield HUDs. The response time data strongly favor developing them. The less dependable error data favor instrument panel displays. The authors believe that the response time data are intriguing enough and the opportunities for improving the quality of the implementation are sufficient to warrant further human factors studies of the merits of full-windshield HUDs. Efforts to develop improved full-windshield HUDs should emphasize designs that reduce opportunities for driver errors. Engineering development of working prototypes should not proceed without favorable results from those experiments.

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APPENDIX A - SEQUENCE OF TEST BLOCKS

	Subject #					
Block	1	2	3	4	5	6
1	2 IP practice	2 IP practice	2 IP practice	2 HUD practice	2 HUD practice	2 HUD practice
2	AS	PeO	AO	UB	AR	AB
3	PS	PO	PeS	AW	UW	UR
4	AO	AS	PeO	AB	UB	AR
5	PeS	PS	PO	UR	AW	UW
6	PeO	AO	AS	AR	AB	UB
7	PO	PeS	PS	UW	UR	AW
8	1 HUD practice	1 HUD practice	1 HUD practice	1 IP practice	1 IP practice	1 IP practice
9	AW	UW	UR	PO	PeS	PS
10	AB	UB	AR	AS	PeO	AO
11	UR	AW	UW	PS	PO	PeS
12	AR	AB	UB	AO	AS	PeO
13	UW	UR	AW	PeS	PS	PO
14	UB	AR	AB	PeO	AO	AS
Block	7	8	9	10	11	12
1	2 IP practice	2 IP practice	2 IP practice	2 HUD practice	2 HUD practice	2 HUD practice
2	PO	PeS	PS	AW	UW	UR
3	AS	PeO	AO	AB	UB	AR
4	PS	PO	PeS	UR	AW	UW
5	AO	AS	PeO	AR	AB	UB
6	PeS	PS	PO	UW	UR	AW
7	PeO	AO	AS	UB	AR	AB
8	1 HUD practice	1 HUD practice	1 HUD practice	1 IP practice	1 IP practice	1 IP practice
9	UB	AR	AB	AS	PeO	AO
10	AW	UW	UR	PS	PO	PeS
11	AB	UB	AR	AO	AS	PeO
12	UR	AW	UW	PeS	PS	PO
13	AR	AB	UB	PeO	AO	AS
14	UW	UR	AW	PO	PeS	PS

IP: AS=aerial solid
AO=aerial outline
PS=plan solid
PO=plan outline
PeS=perspective solid
PeO=perspective outline

HUD: AW=aligned white
UW=unaligned white
AR=aligned red
UR=unaligned red
AB=aligned blue
UB=unaligned blue

APPENDIX B - SLIDE CAROUSEL CONTENTS

+ = cross, Y=Y, T=T, R = T right, L=T left
a, b, c are different intersections within the type

Slide Position	Road Scene		Nav Display		Correct Response
1	Y	c	Y	c	same
2	Y	a	R	c	different
3	R	b	R	b	same
4	L	a	Y	b	different
5	T	c	T	c	same
6	R	c	+	c	different
7	T	a	T	a	same
8	+	b	+	b	same
9	+	a	T	a	different
10	R	a	R	a	same
11	Y	c	T	c	different
12	+	c	L	a	different
13	+	c	+	c	same
14	+	a	+	a	same
15	T	a	R	b	different
16	Y	b	L	c	different
17	+	b	R	a	different
18	L	b	+	b	different
19	T	b	T	b	same
20	L	c	L	c	same
21	R	b	L	b	different
22	L	c	T	b	different
23	T	b	Y	a	different
24	Y	a	Y	a	same
25	T	c	+	a	different
26	Y	b	Y	b	same
27	L	b	L	b	same
28	R	a	Y	c	different
29	R	c	R	c	same
30	L	a	L	a	same

APPENDIX C - CONSENT FORM

Driver Responses to a Street Information System

Participant Consent Form

We are working on a system to show drivers information about local streets to help them when they are lost. A well designed system can be used at a glance, so people can concentrate on driving. Responses from typical drivers such as you, will help identify the best way to show this information.

While sitting in a driving simulator, you will respond to slides of displays by pressing buttons. A computer will record how long it takes to respond and the errors made. We may videotape this session, but only if you allow us. We will not release any identifying information, so your responses will remain confidential.

The experiment takes about 1-1/2 hours for which you will be paid $15 dollars. There will be 1 scheduled break midway through. If you have any problems completing this experiment, you can withdraw at any time. You will be paid regardless.

I have read and understand the information above.

Print your name	Date
Sign your name	Witness (experimenter)

APPENDIX D - BIOGRAPHICAL FORM

University of Michigan Transportation Research Institute
Human Factors Division

Biographical Form

Subject: ☐

Date: ☐

Name: ______________________________

Male Female (circle one) Age: __________

Occupation: __________ Retired or student: List former occupation or major

Education (circle highest level completed)

some high school	high school degree
some trade/tech school	trade/tech school degree
some college	college degree
some graduate school	graduate school degree

What kind of car do you drive the most?

Year: ________ Make: __________ Model: __________

Annual mileage: __________

Have you ever driven a vehicle with an in-vehicle traffic information or navigation system?

No Yes, in an experiment Yes, elsewhere

Have you ever driven a car with a Head-Up Display (HUD)?

No Yes ---------> If yes, does your car have a HUD? Yes No

In the last 6 months, how many times have you used a map?

0 1-2 3-4 5-6 7-8 9 or more

In the last 2 weeks, how often did you rely on traffic information reports to get to a destination quickly and efficiently?

0 1-2 3-4 5-6 times 7 or more

How often do you use a computer?

Daily A few times a week A few times a month Once in awhile Never

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

Vision correctors? Yes / No

__________ if yes, name type

APPENDIX E - PROCEDURE

Navigation Screen Study

Prior to arrival of participant:
Make sure there are blank consent forms, bio forms, support voucher, the system ranking form, and money for payment.

Check Lab Ex 2 Block listing and note the proper order of slide carousels.

- Plug in light behind wall.
- Put red reflector stand in front of wall in line of HUD.
- Put black paper over keyboard labels.
- Switch on two power strips by PC, including all individual plug switches.
- Turn on computer.
- Switch on third power strip.
- Check that the variacs are on.
- Turn on florescent light by PC.
- Put shape practice carousel on IP projector and road scene carousel on wall projector.
- Set shutter and kodak controller switches to IP.
- Run FOCUS2.
- Switch on black power supply.
- Open both shutters and advance to slide 1. Check alignment and focus of IP and wall projections. Send projectors to zero. Quit FOCUS2.
- Put shape carousel on HUD projector.
- Set shutter and Kodak controller switches to HUD.
- Run FOCUS2. Open shutter 1 and advance to slide 1. Check alignment and focus of HUD. (This may be easier to fix with black box lifted off.) Send projectors to zero. Quit FOCUS2.
- Verify that HUD projector is zeroed.
- Check which display subject does first. Turn shutter and controller switches accordingly.
- Put shape practice carousels on wall projector and correct display projector.
- Put display carousels in order. Two stacks of three. If subject begins on IP, put display carousels on rear table. If subject begins on HUD, put display carousels on front wooden table.
- Go to NAV directory. Run RT2P. Load N1P1.INP. Make output file NAV2S#.OUT
- Check that keys 3 and 4 are exposed on keyboard.
- Turn on power supply behind driver's seat.

Complete as much of the bio form as possible.

When participant arrives:

Are you ____? Hello, my name is ______ and I am one of the experimenters working on the street information study. Before we get going I would like to note this experiment takes approximately 1 and a half hours and you

will be paid 15 dollars for your time. If you would like to visit the rest room, now would be a good time to do so. Also smoking is prohibited in this building, so please refrain from doing so.

Go into lab. Flip "Experiment in Progress" sign over on door.

The purpose of this experiment is to determine the best way to present drivers with information regarding road intersections. The results of this study will be used for designing systems for use in future vehicles. Since you will be driving those vehicles, your opinion is important.

Before we start, there is some paperwork to complete. First, you need to sign this official consent form the university requires us to give you, which basically repeats in writing what I just said.

Have participant sign consent form.

And, we need to know a little more about you.

Fill out bio form with subject.

Test subjects vision. Make sure both eye switches are on.

Have participant sit in buck.

We want to know how a computer should tell drivers where they are and where the display should be in the car.

You will sit here in the driver's seat and projected on the wall in front of you will be road scenes. At the same time on one of the small screens will be shown our street information system. Your task is to decide if the scene shown on the car screen matches the scene shown on the wall, and to respond by pressing a button.

Position yourself as if you were driving. Can you see the red reflector in front of the wall? Can you see it without stretching?

Adjust seat if necessary, using electric controls.

Lay your hand on the black keyboard on your right with these two fingers on the two keys. Are you comfortable? Would you like the seat moved at all?

Adjust seat if necessary.

Move red reflector out of way behind wall.

Practice on IP/HUD

Before we get into the actual study, you need practice at responding to slides. In these two practice runs, the slides show shapes: squares, circles, triangles, etc. On the gray wall, there will appear a large shape and at the same time a shape will be shown (on the small screen in the middle of the car)/(superimposed on the wall). If the shapes are the same, press the left button. If they are different, press the right button. Touch respective fingers. **Half of the slides will match, and half will not match. The shapes on can be solid or outline, only the type of shape has to match. Also, the shapes on the wall might not be aligned.** Show unaligned demo. **For example, if both are triangles, they match. If you get one wrong you will hear a tone informing you.**

Do you have any questions?

Answer questions.

There will be 56 slides in each of these two practice blocks. Remember, same (wiggle index finger right hand) **different** (wiggle middle finger right hand).

I am going to turn off the lights now.

Turn out lights.

Are you ready?

Do 2 practice blocks.

IP/HUD test

Move shape carousel to other display projector (IP to HUD, or HUD to IP), put road scenes in wall projector, and put first display carousel on proper projector.

Now it is time to respond to the real system. On the wall will appear slides of intersections. On the (small screen inside)/(wall) will be a simulated image from a computer. If they match, press the left (or same) button as you did in practice. If they are different, press the right button. Try to respond as rapidly and accurately as possible.

Point to the buttons.

Don't worry about the street names matching. When the intersections match, the street names will also. We are only interested in evaluating the display of the intersection. Again half of the slides will match, and half will not match.

Do you have any questions?

Answer questions.

This set is 60 slides. There will be six sets and then a break.

RUN TRIALS IN THE ORDER SPECIFIED IN SUBJECT LISTING

As carousels are used place them on the car seat in order starting on the edge closest to the front of the room.

Give feedback at the end of each block (You are doing fine, you are making too many mistakes, etc...)

When finished, put shape carousel on wall projector.

Quit RT. Switch shutter and Kodak controller to other display. Re-run RT2P with N1P3.INP.

TAKE A BREAK

Now we are going to move to the location (on the wall)/(inside of the car). To get used to it, there will be one practice run again with the shape slides.

Do 1 practice trial.

RUN REMAINING TRIALS IN THE ORDER SPECIFIED IN SUBJECT LISTING

Take carousels from car seat in order from one closest to front of room. Stack used ones on table closest to display projector.

Quit RT.

Turn on lights. Show subject pictures of each system in each location with signs on table reading "best" and "worst".

I want you to rank these systems from best to worst, by placing them in a row on the table with the one you like the best closest to the sign that says "best", and the one you like the worst closest to the sign "worst".

Have subject rank. Write down ranks and mix design ranking sheets.

Have subject fill out support voucher and pay subject.

After subject leaves:

Take disk to NCR in MW's office and copy file to 3 1/2 floppy and copy to Mac hard drive **Nav2 output** folder.