THE EFFECT OF HUD WARNING LOCATION ON DRIVER RESPONSES

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SUMMARY

This study investigated the effect of head-up display (HUD) location on response time and detection probability of HUD warnings. Twenty-four subjects, sitting in a driving simulator, watched a projected videotape of driving in traffic on a real road. The subjects pressed a key whenever they detected predetermined events in the road scene (passing cars, leading car signals, or road signs). In addition, the subjects pressed a key when a warning triangle appeared on the HUD at one of 15 locations.

Response times to HUD warnings, and detection probability, varied with warning location. The mean response times ranged from 842 to 1390 ms with the fastest response time 5° to the right of the center. The HUD task did not significantly interfere with detection of road events. When the HUD task was added to the driving task, response times to car signals increased only slightly (from 1175 to 1260 ms) and the detection probability did not change.

INTRODUCTION

HUDs have been used in motor vehicles to show speed, vehicle malfunction warnings, radio settings, and other information. Presenting information on a HUD instead of an instrument panel display maintains the direction of gaze toward the road, enhancing driving safety. When drivers look at the instrument panel, they may not see an external event needing 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 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, to potential automotive safety benefits, and to driver convenience, limited production of automotive HUDs has occurred (1988 Nissan Silvia, 1988 Oldsmobile Cutlass). To support development, several studies have been conducted to assess the benefits of having HUDs in automobiles and assist in their design. These studies and other studies relevant to automobiles have examined the following issues: the general benefits of HUDs (1,2,4,7); display location (4,6); image distance (5,9); size (5); color (5); and brightness and contrast (3,8). See reference (10) for a summary.

The literature suggests that the ideal location for a HUD is directly ahead of the driver, about 10° below the forward line of vision. Unfortunately, no studies in the literature have examined a sufficient number of locations to develop an empiric relationship between location and some performance measure. 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 experiment described herein was conducted (10). This experiment examined three questions:

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 (a) interfere with the detection of, and (b) alter response time to events on the road?
3. What are the best and worst locations for a HUD warning as reported by the subjects?

TEST PLAN

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. Subjects were checked for visual acuity, depth perception, peripheral vision, and color vision abnormality. Four subjects had driven an automobile with a HUD.

The HUD task and road events

To determine the effect of HUD location on visual performance, warning triangles were presented in 15 locations (3 rows of 5 columns, Figure 1). Only one triangle appeared at a time. All the subjects were seated in the vehicle mockup so that their eye positions were fixed at common coordinates and that their line of sight straight ahead overlapped the centermost triangle with the lead car. The amber-colored 4.2 cm equilateral triangles were spaced approximately 5° apart. The focal distance of the triangles ranged between 94 and 106 cm. The contrast ratios, independently measured for each occurrence, ranged from 1.3

to 6.5, where contrast ratio was defined as:

$$\text{contrast ratio} = \frac{\text{combined target and background luminance}}{\text{background luminance}}$$

The average contrast ratio of each location ranged from 1.3±0.0 (C1) to 3.1±1.1 (E2). Typical luminance values of some objects in the road scene were from 4.4 cd/m^2 (sky) to 0.44 cd/m^2 (lead vehicle). The average luminance of the HUD triangle was 1.62 cd/m^2.

To draw attention to the road, subjects responded to three types of events: (a) passing vehicles, (b) taillights of the lead car, and (c) road signs. The three types of events spanned the screen from left to right, respectively, leading to scan patterns believed to resemble real driving. Subjects pressed a button when either (a) the rear of a vehicle passing in the left lane was aligned with the rear of the lead car, (b) the brake lights or the turn signal lights of the lead car were activated, or (c) a yellow, diamond-shaped sign on the right side of the road was aligned with the lead car's rear bumper. To provide for the desired test duration, tapes of four highly similar roads were presented.

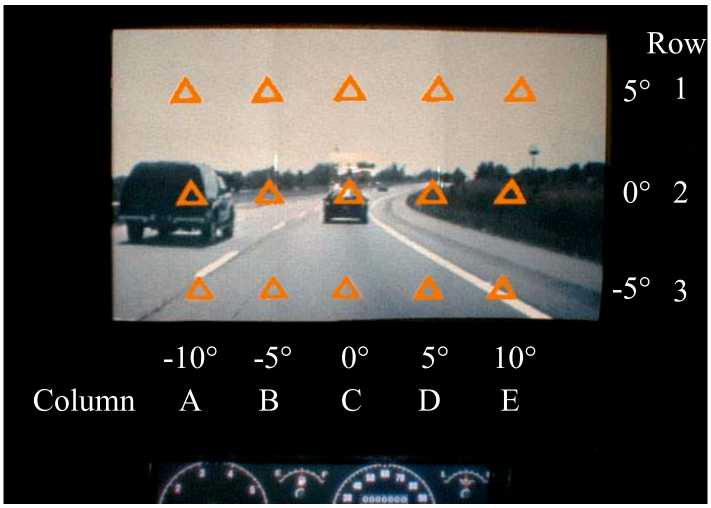

Figure 1. All 15 locations of the HUD activated with the road scene.

The HUD warnings were randomly distributed across the road with an interstimulus interval time of 25±5 s. The road events could not be perfectly controlled due to small differences in congestion and a varying number of road signs. However, the mean time between two events was similar for all four roads (6.5±4.5 s). 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.

Test materials and equipment

The road scene was recorded on US-23 — a 105 km/hr (65 mi/hr) divided expressway — with a camera just below the rear view mirror. A microphone was placed under the hood of the car to collect engine, traffic, and road noise. The lead vehicle in the road scene activated its brake lights and turn signal lights in random order and at random times as determined in real-time by a computer program. 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 (Figure 2). The sheet allowed the subjects to see a reflection of the HUD images that originated from two flat-panel LCD monitors lying on top of the dashboard. The videotapes of the road scene were played on a VCR and projected onto a 2.4 x 3.6 m screen, 6 m in front of the subject.

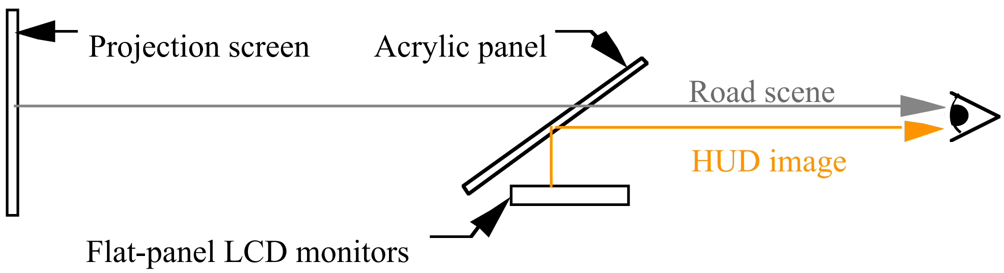

Figure 2. Image paths

Psyscope software (v. 1.2.1 PPC, Carnegie Mellon University) was used to display HUD warnings and to collect subjects' responses. Subjects responded by pressing a two-button keypad: one button for the head-up display, and one for all events in the road scene. Several cameras recorded the subjects' fingers, the LCD monitors that displayed the HUD warnings, and the subject's face during the experiment.

<u>Test activities and their sequence</u>

After a training session, baseline road events and HUD data were collected. For the road events baseline, subjects responded only to road events for an 8 min segment of Road 2. Then subjects responded to both road events and the HUD. The order of the four runs was randomized for each of the six subjects within the age and gender groups. Similar baseline data was collected after the test conditions. Subsequently, the subject filled out a questionnaire to evaluate the HUD and tasks used in the experiment. The subjects were also asked to identify the three best and three worst of the 15 locations for a HUD warning.

RESULTS

Approximately 19,000 data points were obtained for all runs of all subjects. For the 64 missing HUD responses, a response time of 10000 ms, the maximum allowed, was assumed. HUD response times were transformed using a natural log (ln) to provide normality prior to the analysis — an assumption of the analysis of variance (ANOVA). The floor effect, which had caused the original distribution to be asymmetric, was almost completely eliminated by the transformation, although a slight asymmetry between the right and left tails remained.

Responses to HUD warnings while scanning videotaped roads

Ninety-five percent of older drivers' responses were under 6680 ms and 90 percent were under 2830 ms, while 95 percent of younger drivers' responses were under 1930 ms and 90 percent were under 1280 ms.

The effect of HUD warning location on responses to HUD warnings

For the 15 locations explored, the difference between the three rows was highly significant (p=0.0001). Column differences were marginally significant (p=0.055), and the interaction between rows and columns was highly significant (p=0.0001).

Each bar in Figure 3 represents the mean across subjects of the transformed mean response times for each of the 15 HUD warning locations. A post-hoc test showed a significant pair-wise difference between E1, A3, D1, and each of the other locations (p=0.0001). D2, the fastest response time of all tested locations, was significantly faster than all locations over 950 ms. Overall, drivers responded more slowly to HUD warnings at visual angles farther from the center.

The detection probabilities for each location across all subjects were also analyzed — the portion of 192 detection opportunities that was not detected within 10 seconds. 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 95 percent or lower. The eccentricity hypothesis (locations at greater visual angles from the line of sight required more time) explained some, but not all, of the results.

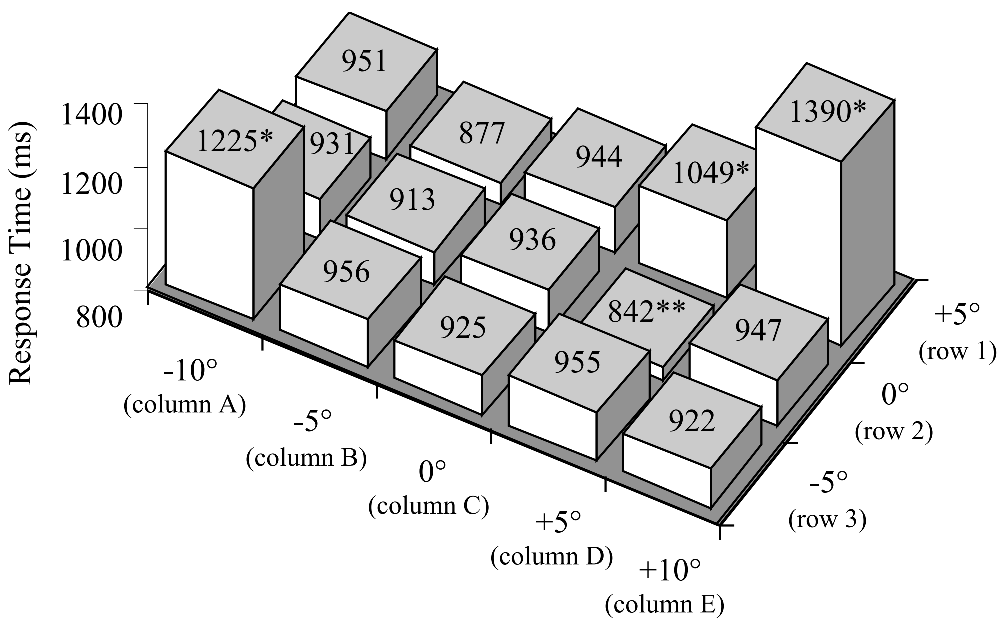

Figure 3. HUD response time for each location
(*=significantly different than all others, **=significantly different than some)

The effect of age on responses to HUD warnings

Older drivers responded to HUD warnings significantly slower than younger drivers (p=0.0008, 826 vs. 1153 ms, a 40 percent difference). The interaction between row and age, and column and age were both significant (p=0.04 for both) with older drivers responding relatively more slowly to locations on the right (Figure 4) and showing greater differences between rows.

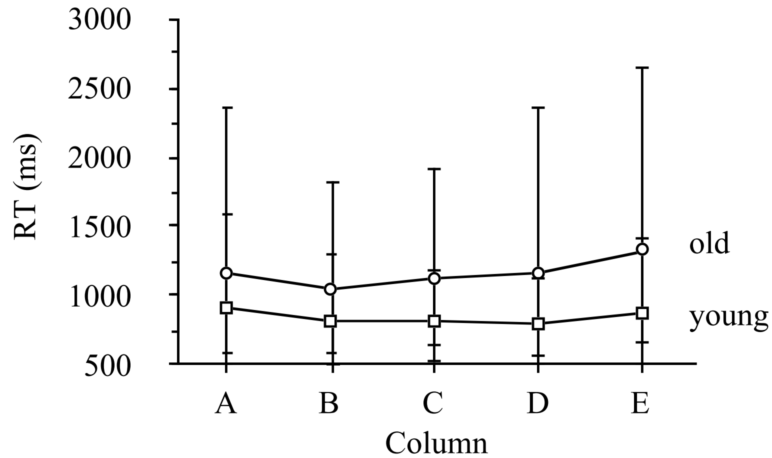

Figure 4. Effect of column and age on HUD response time

Learning effect and Trial 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). Variance also decreased with practice.

<u>HUD warning detection with and without scanning videotaped roads</u>

To examine the effects of learning, the pre-experiment baseline response times to HUD warnings alone (515 ms) were compared with the post-experiment baseline means (566 ms), a difference of marginal significance (p=0.058). Hence, the 120 intervening HUD warning trials slightly fatigued subjects, but given the small effect size, learning was ignored in further analyses.

Of interest was the impact of combining the driving task with the detection of HUD warnings. The mean response time for the HUD detection task alone was 540 ms versus 976 ms when the road detection task was also present (an 80 percent increase), an extremely significant difference (p<0.0001).

Figure 5 shows these two learning and task combination effects. 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. If the experiment had been run without a driving task (as in the 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 of HUD location effects should include a driving component.

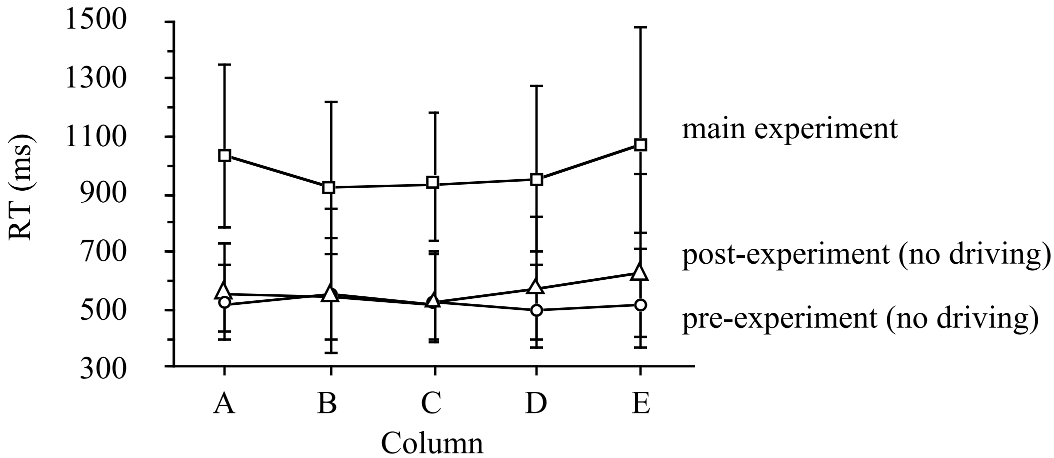

Figure 5. HUD response time during the main experiment and during the baselines

Luminance contrast

In this experiment, HUD warning luminance contrast was confounded with warning location due to resource limitations. HUD warnings in the upper left had an average contrast of 1.5±0.1 due to bright sky in the background, whereas HUD warnings in the lower right had an average contrast of 3.0±1.0 due to a dark background of road or bushes. In a regression of HUD warning response times, there were no tendencies for response time to be correlated with contrast.

Responses to car signal lights

An ANOVA of the response probabilities to lead vehicle signal lights revealed that the effects of age (p=0.007) and run (p=0.004) were significant, but not gender. Younger subjects were more likely to detect signal lights than were older subjects (p=0.92, versus p=0.81). There was an improvement in detection probability until run 3, and then a drop in the last run.

The ANOVA of response times to car signals revealed significant effects of roads (p<0.0001) and age (p=0.02). 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 other events and the timing of events.

The effect of age and HUD task on car signal lights detection probability

Of particular interest was whether providing a HUD interfered with the detection of car signals. There was no difference between the response times to detecting car signals alone (the baseline data, 1200 ms in the pre-test, 1150 ms in the post-test) versus when a HUD was present (the experimental data, 1260 ms, a difference of less than 10 percent). There was a marginal difference in detection probability between those three points (p=0.055), and a significant interaction of order with age (p=0.017). Older drivers kept improving their detection probability throughout the experiment (0.80 in the pre experiment baseline, 0.88 in the main experiment (HUD warnings present), 0.90 for the post-test baseline).

Detection probability of road events

For the detection probability of events other than car signals (passing cars on the left side and road signs on the right side), there was a slight but significant (p=0.036) age difference (0.83 for older drivers, 0.89 for younger drivers). There was essentially no difference between the pre and post baselines (0.73 versus 0.72).

Subject preferences

After the experiment, subjects were asked to choose the three best and three worst locations for HUD warnings. Figure 6 presents the subjective preferences computed as the number of times each location was voted "best" minus the number of times it was voted "worst." 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.

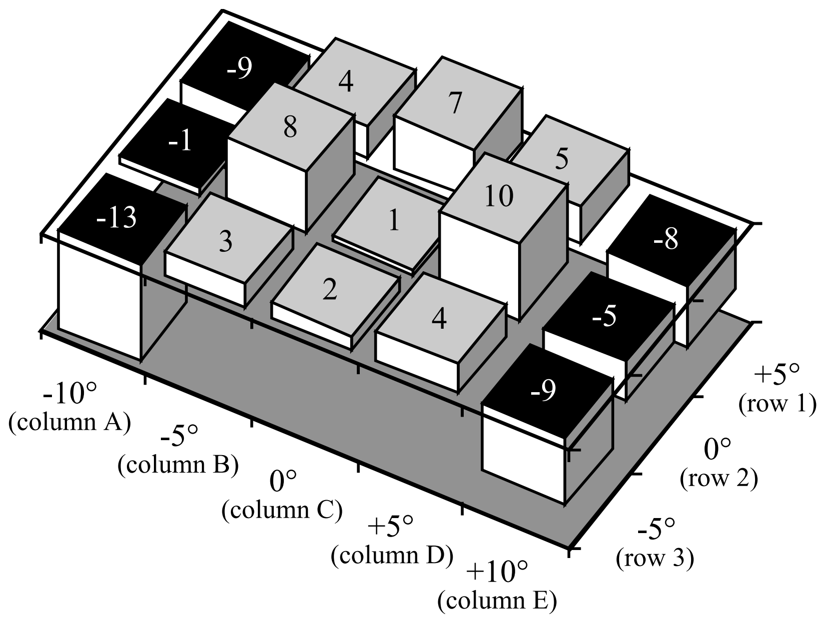

Figure 6. Subjective preference for location

Subjective evaluation of the task

The subjects rated the difficulty in detecting HUD warnings, the interference of HUDs with road events, and the potential usefulness of HUDs for drawing on a visual-analog scale. The rated difficulty in detecting HUD warnings was very easy (1.1 of 6); the interference of warnings with road events detection was low (2.0 of 6); and the usefulness of warning triangles to draw attention was high (5.1 of 6). Subjects also rated the difficulty of each task. In this case, the difficulty of the driving task (2.0) and HUD task (1.2) was equal to the sum of the difficulty of each task (3.2), that is, task difficulties were additive.

CONCLUSIONS

How does the location of an automotive HUD affect the detection probability and response time to HUD warnings while driving?

As expected, the response times to HUD warnings, and to a lesser extent, the detection probability, varied with HUD location. 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. 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.

Although response times and detection probability of the different center locations were generally similar, the fastest response time was located 5° to the right of the center (D2). There were clear age differences with 10 percent of older subjects' responses exceeding 2830 ms while only 3 percent of younger subjects' responses exceeded this value.

The eccentricity effects were more pronounced for older subjects. Older subjects took longer and more frequently missed the HUD warnings in the corners. 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 (a) interfere with the detection of, and (b) alter response time to events on the road?

If the HUD warnings interfered with detecting road events, HUD warnings may not be worthwhile to provide. Although some interference occurred, response times and detection rate of events on the road were not significantly worse when the HUD detection task was performed concurrently. Therefore, detecting a HUD warning (which disappears after detection) does not interfere with the detection and response time to events on the road.

However, several caveats should be kept in mind. First, the workload was probably lower than when actually driving a motor vehicle because subjects in the experiment were not actually controlling the vehicle. Second, subjects were alert for HUD warnings, thus reducing the effect of surprise. Third, HUD warnings occurred rather frequently 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 results also indicate that there is a difference between responding to only HUDs and responding to HUDs in a driving context, especially for older drivers. Therefore, future HUD experiments should always be conducted in a driving context.

What are the best and worst locations for a HUD warning as reported by the subjects? The corner locations were perceived to be worse than central locations, as predicted by the eccentricity hypothesis, but also disliked the center location and the lower center. In general, drivers did not like locations that were farther than 5° horizontally from the center and preferred locations that did not overlap with locations where important events occurred (e.g., in the exact center).

ACKNOWLEDGEMENT

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