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THE EFFECTS OF AUTOMOBILE HEAD-UP DISPLAY LOCATION FOR YOUNGER AND OLDER DRIVERS

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16. Abstract

We performed a laboratory study using simulated road scenes and simulated automobile HUDs to examine the effect of HUD location on a driver's ability to discriminate the presence or absence of a pedestrian in or near the path of the vehicle. We showed subjects brief presentations of road scenes with HUDs superimposed at three different positions: 4, 9, or 15 degrees below the horizon. Subjects had to perform two tasks for each presentation, one based on the road scene (presence or absence of a pedestrian) and one based on information in the HUD (direction of a future turn as indicated on a map). Our intent was to assess how HUD location affected a driver's sensitivity to the outside environment while he or she was paying attention to the display. We therefore instructed subjects to emphasize accuracy on the HUD task to the extent that the demands of the two tasks conflicted. Because we believed that there would be important differences between young and old subjects in the effect of HUD location, we included subjects in two age groups, which averaged 21.3 and 66.1 years old, respectively.

Performance on the map task was only slightly affected by HUD location, whereas performance on the pedestrian task deteriorated markedly when the HUD was further below the horizon. This is consistent with the instructions for subjects to maintain high accuracy on the HUD task. The change in performance on the pedestrian task was significantly greater for the older than for the younger subjects. This finding is consistent with other results showing that older people have more difficulty in visual divided-attention tasks.

These results provide quantification of the benefits of HUDs in maintaining sensitivity to the outside environment when a driver is attending to vehicle displays. The results suggest that those benefits are significantly greater for older than younger drivers. The larger question of how drivers should distribute attention between the road and vehicle displays for optimum safety is not addressed by this study.

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Introduction

Drivers should keep their eyes on the road. That is the central demand of the driving task. Nevertheless, drivers are sometimes unable, or unwilling, to keep their eyes and visual attention focused on the environment ahead of them. Head-up displays (HUDs) can reduce the conflict between the need to watch the road and the need, or desire, to look at various vehicle displays by placing those displays so that they appear, in terms of visual angle as seen from the driver's viewing position, close to the direction of travel.

The closer a display is to the direction of travel, the more a driver is able to maintain some awareness of the road ahead while looking at the display. But when the angular separation between the display and the direction of travel is very small, the display may directly interfere with the driver's ability to see objects and events on the road by masking them. This conflict makes it important to understand how the main benefit of HUDs—maintaining sensitivity to the road while looking at a display—varies with angular position of the HUD relative to the straight ahead.

Although that issue is important for understanding and optimizing the benefits of HUDs, it has received surprisingly little attention in the open literature on HUDs. Much of the human factors research on HUDs, which is primarily related to aircraft HUDs, was recently reviewed by Weintraub and Ensing (1992). A somewhat more extensive review of the portion of the literature specific to automotive HUDs was made by Harrison (1994), who identified six studies with results relevant to the location of an automotive HUD. None of those studies provides a direct answer to the question of how HUD location influences a driver's sensitivity to objects and events on the road. Several studies did not address the issue of objective visual performance at all; they instead based recommendations for HUD location on subjective measures such as subjects' rating of "annoyance" as a function of HUD location rather than measuring objective performance in a dual-task situation (Inzuka, Osumi, & Shinkai, 1991). Although subjective measures are probably useful for HUD design, it would be good to supplement such measures with objective assessment of performance on dual tasks similar to the demands faced by a driver who is looking at a HUD and trying to maintain sensitivity to the road at the same time. Several studies did employ such dual-task methods (Okabayashi et al., 1989; Okabayashi, Sakata, Furukawa, & Hatada, 1990; Sakata, Okabayashi, Fukano, Hirose, & Ozono, 1988). However, those studies all used artificial stimuli that have traditionally been used to measure acuity, and also did not fully describe the tasks or the resulting data. A recent study in the domain of aircraft HUDs addressed the effect of HUD location on simultaneous performance of two simulated flying tasks: maintaining altitude using the HUD and following a path marked by objects on the ground (Foyle, McCann, Sanford, & Schwirzke, 1993). However, the dependent variables in that study were measures of performance (variability in altitude maintenance and path keeping) on relatively long-term, complex tasks. Thus they may reflect mechanisms, such as strategies for allocating attention, that are idiosyncratic to the specific tasks involved.

We therefore undertook the present study to quantify, for realistic road stimuli, how a driver's sensitivity to the road varies with the angular position of a HUD while the driver is looking at, and devoting attention to, the HUD. This study does not address issues such as when HUDs should be used, what they should display, or the relative importance of paying attention to vehicle displays versus the road for safe and efficient driving. It was intended to provide information about the relatively basic question of how display location affects sensitivity to the road when a driver is, for whatever reason, looking at and attending to the display.

In a laboratory study we showed subjects brief presentations of road scenes with simulated HUDs superimposed on them, and required them to perform two visual tasks for each presentation, one based on the information displayed in the HUD and one based on the road scene. The HUD was presented at one of three locations relative to the road scene, and we measured performance of both tasks as functions of HUD location. Because we wanted to simulate a situation in which a driver is looking at and attending to a vehicle display, we chose a relatively complex HUD stimulus—a simulated navigation display consisting of a road map—and instructed the subjects to perform the HUD task first and to give it primary importance. The subject's first task was to report the direction (right or left) of a future turn portrayed in the map. The road scenes were photographs of actual roads taken from a driver's point of view. The photographs were taken in pairs that were identical except that in one member of the pair the road was clear and in the other it was partially obstructed by a posed pedestrian model. The subject's second task was to report whether the road was clear.

The task used in this experiment is very similar to a divided-attention task used by Ball and her coworkers (Ball, Owsley, & Beard, 1990) to measure the "useful field of view" (UFOV). Older people have smaller UFOVs than younger people (Ball, Beard, Roenker, Miller, & Griggs, 1988). Furthermore, among older drivers, the extent of the UFOV has been shown to be predictive of accident involvement (Ball, Owsley, Sloane, Roenker, & Bruni, 1993). Because we expected that the effect of HUD location would be different for younger and older drivers, we included a group of each in the study.

Method

Subjects

There were 24 subjects: 12 in a younger group (aged 18 to 25 years with a mean of 21.3), and 12 in an older group (aged 60 to 74 with a mean of 66.1). An effort was made to ensure that the sample would be approximately balanced by sex, but equal representation was not required. In the younger group there were seven males and five females; in the older group there were eight males and four females. The subjects were paid for their participation. All subjects were licensed, active drivers. By self report, the younger group's annual driving mileage ranged from 4,000 to 40,000 miles with an average of 14,250. The older group's mileage ranged from 2,000 to 20,000 with an average of 11,960. None had previous experience with HUDs.

Equipment

Schematic diagrams of the laboratory setup are shown in Figures 1 and 2, both of which accurately depict, in reduced scale, the projection and viewing geometries used in the experiment. The subjects were seated so that their eyes were 148 cm from a white, diffusely reflecting screen mounted on a wall of the laboratory. Subjects' seated eye heights were about 115 cm above the floor. A 40 W incandescent lamp was directed at the wall behind the subject to provide a low level of indirect illumination on the projection screen and throughout the laboratory.

Behind and to the left of the subjects were two identical random-access slide projectors, mounted in a rack one above the other. The upper projector, which was used to project the simulated HUD, was 115 cm above the floor (measured to the middle of the lens). The lower projector, which was used to project road scenes, was 25 cm lower.

As shown in Figure 2, the optical axes of the projectors were nearly perpendicular to the screen with regard to vertical aim. The road projector was aimed so that the horizons in the road slides would be projected on the screen, on average, at the same height (115 cm above the floor) as the subject's eyes. The HUD projector was aimed to project on exactly the same area as the road projector.

As shown in Figure 1, the horizontal aim of the projectors deviated by about 21 degrees from a line perpendicular to the screen. This was necessary to allow the subjects to view the projected road images from a relatively close position, at which they would subtend the same visual angle as they had in reality subtended from the position of the camera that captured them (about 24 degrees vertically and 36 degrees horizontally). The oblique aim resulted in some geometric distortion of the projected images (e.g., keystoneing caused the height of the images of the slides to increase from 63 cm at the left edge to 70 cm at the right edge); however, in the judgment of the authors the distortion was too subtle to distract the subjects or otherwise affect their performance.

Both projectors were equipped with electronically controlled shutters.

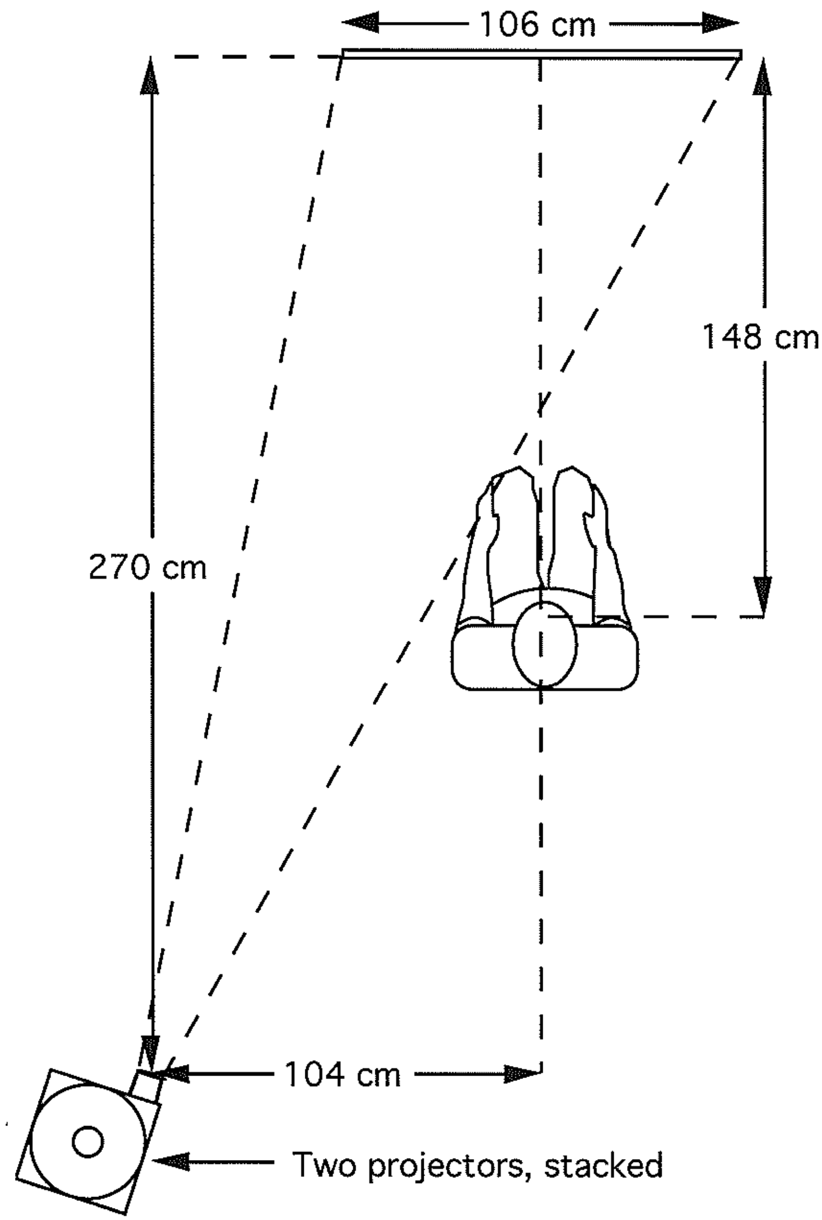

Figure 1. An overhead view of the laboratory setup. All distances are to scale. The single image of a slide projector in this figure is meant to represent two identical random-access slide projectors, stacked one above the other, that projected the road slides and HUD slides onto the same screen.

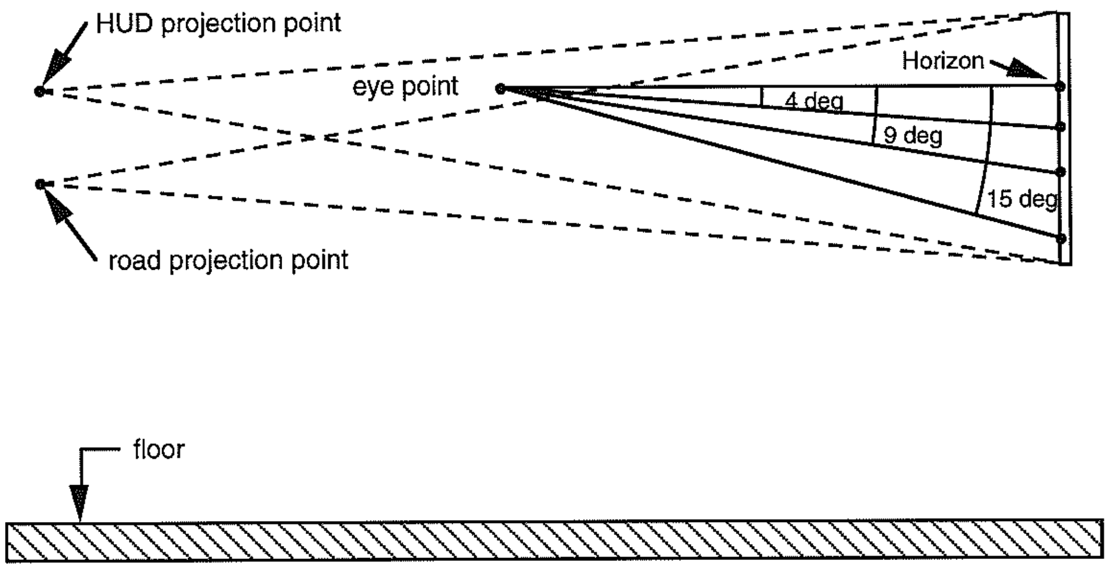

Figure 2. A side view of the projection lines and sight lines used in the experiment. All distances are to scale. The subject's eye point was level with the point at which the horizons of the road slides, on average, appeared on the projection screen. The lens of the projector used for the HUDs was also at that level. The road-slide projector was slightly lower. The angles between the average horizon line and the centers of HUD maps at the three HUD locations are illustrated.

Stimuli

Two sets of 35-mm slides were used in the experiment: road slides and HUD slides. Each stimulus presentation involved two slides, one slide from each set, superimposed by projection onto a single screen by two projectors. The subject's view of these combined stimuli is depicted schematically in Figure 3.

The road slides depicted typical road scenes from a driver's point of view. They were made by photographing two-lane roads in the Ann Arbor area that were approximately straight and level. The photography was done in daylight, with no traffic present, using color slide film. The camera was mounted in the roadway in a location that would be momentarily occupied by the eyes of a typical passing driver: 1.1 m above the surface and slightly offset to the left of the center of a lane. The horizontal aim of the camera was parallel to the road and the vertical aim was 5 degrees down. The camera was fitted with a 50 mm lens, which has a field of view of approximately 24 degrees vertically and 36 degrees horizontally. Thus, the horizon appeared slightly above the centers of the slides, and the field of view of the camera extended from 7 degrees above vertical to 17 degrees below vertical (corresponding to a nearest visible point on the pavement approximately 3.3 m from the camera).

Each of 6 road scenes was photographed twice, yielding 12 road slides in all. One version was completely clear of potential obstacles in or near the lane from which the scene was photographed (no pedestrians, animals, or vehicles). The other included a single pedestrian about 25 m from the camera, walking across the road and just entering the camera's lane from the left or right. The two photographs were taken several seconds apart to allow enough time for a pedestrian model to enter the scene, but they were otherwise identical.

The rectangles in Figure 3 indicate the sizes and positions of pedestrian images. Because the roads were not all perfectly straight and level, the relationships between these rectangles and the single, idealized set of horizon and lane-demarcation lines shown in Figure 3 do not exactly depict the corresponding relationships to the actual horizon and lane-demarcation lines on the individual slides. The locations of the pedestrians relative to the three HUD map locations, however, are accurate.

The HUD slides had images of road maps that consisted of a few simple lines and symbols. The slides were produced by printing black map elements on white sheets of paper that were then photographed and developed as negative images using Kodak Ektagraphic HC slide film (Kodalith), which allows very high density black backgrounds. Thus, on a slide the elements of a map were clear areas against an almost opaque background. When a HUD slide was projected superimposed with a road slide, the map image therefore appeared as a luminance increment on the road image, but the background portion of the HUD slide was dark enough that the contrasts in the road slide were almost unaffected.

Ten of the HUD maps are illustrated in Figure 4. There were 120 different HUD slides in all, generated by systematically varying (as explained below) certain aspects of the 10 "base" maps illustrated in Figure 4. An arrowhead appeared in the same position and orientation in the lower portion of each map. Subjects were instructed that the arrowhead was an indicator of their present location and direction of travel. In all maps, the arrowhead was located on a straight, vertical line running down the middle of the map. (All maps thus depicted the subject as traveling on a straight road, and they were therefore consistent with all of the scenes depicted in the road slides with which they were paired.) All maps had a single dot that subjects were instructed to interpret as indicating the location of their destination. The location of the dot and the configuration of side roads varied from slide to slide. The dot was always located on a side road rather than on the central, straight road on which the subject was supposedly located. The maps were loosely based on streets in Ann Arbor, but we did not intend for subjects to interpret them as representing actual locations. The scale of the maps was not specified.

The complete set of 120 HUD slides was produced by generating 12 versions of each base map, consisting of the factorial combination of the following three variables: (a) the side of the slide on which the destination dot was located (right or left of the central road, achieved by reflecting the entire image around its vertical axis), (b) the direction of the final turn that a driver would make when approaching the destination dot from the direction the subject was supposed to be coming (right or left of the side road near which the dot was located), and (c) location of the map on the slide (positioned so that the map would be projected onto one of the three locations illustrated in Figure 3 while the aim of the HUD projector remained fixed). Figure 5 shows the four maps that result from applying the first two of these variables (side of map and direction of final turn) to one of the base maps shown in Figure 4.

The images of both the road slides and the HUD slides on the screen were 66 cm high (24 degrees of visual angle) and 106 cm wide (36 degrees of visual angle). Their lower edges were 68 cm above the floor. The pedestrian images were 11 cm high (4.25 degrees of visual angle). The maps were 9 cm (3.5 degrees of visual angle) in height and width.

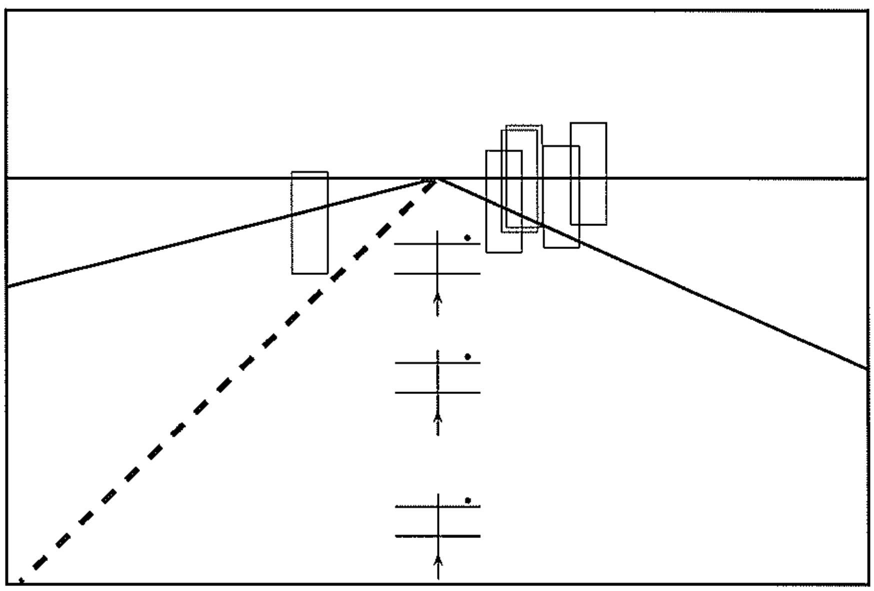

Figure 3. A representation of the subject's view of the superimposed road and HUD slides. The abstract road slide shown here is an geometrically accurate projected view of a straight, level road with 12-ft (3.7-m) lanes, viewed from a position 1.1 m high and slightly offset from the center of the viewer's lane (a typical driver's eye point). The actual road slides were photographs of specific road sites. For illustrative purposes this figure shows a map at each of the three potential HUD locations. In the experiment, only one location was used at a time. The rectangles indicate the positions of pedestrians, for the six slides in which pedestrians were present, relative to the map locations.

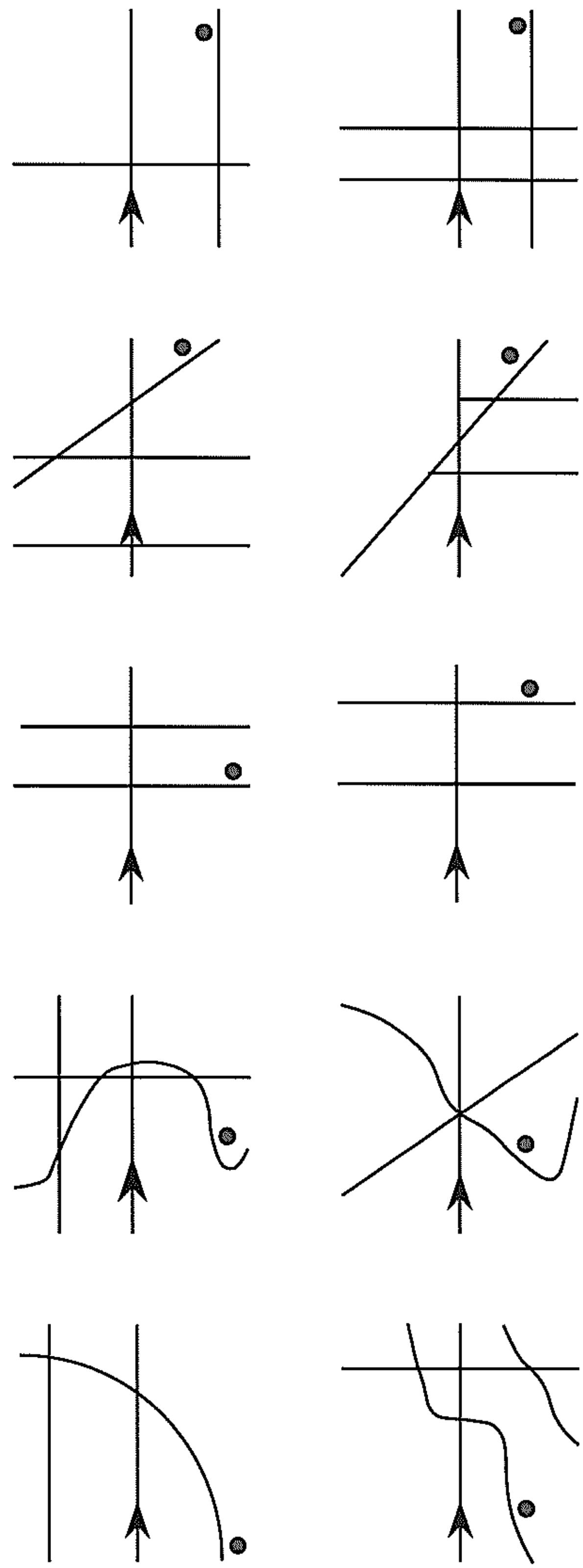

Figure 4. The full set of 10 base maps.

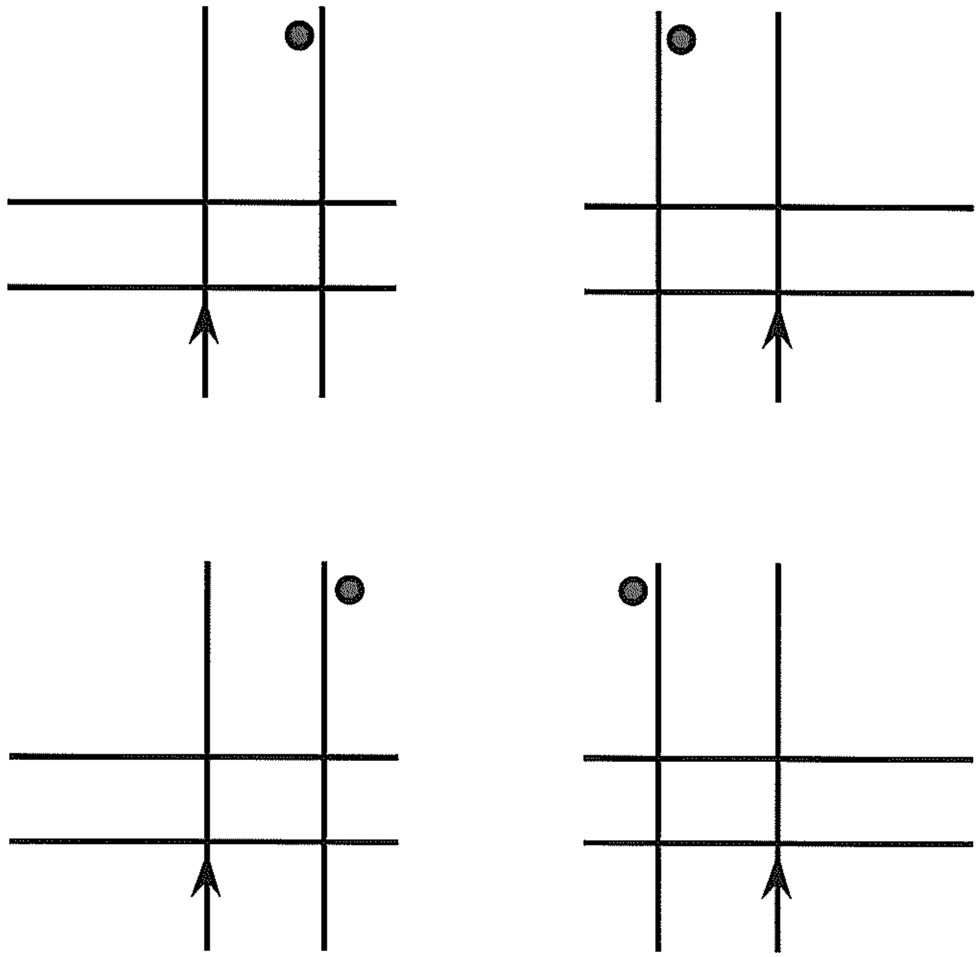

Figure 5. The four maps produced by varying the side of the map on which the destination dot was located and the direction of the final turn to reach the destination, for one of the base maps shown in Figure 4.

Photometry

The background luminance of the screen—illuminated by the lamp that diffusely illuminated the entire laboratory, with both slide projector shutters closed—was 0.17 cd/m^2. The luminance of the strokes of the projected HUD images was approximately 30.4 cd/m^2 (with the background lamp on, but no road slide). The luminance of portions of the screen adjacent to the strokes (including the effects of the background lamp and of light penetrating the nominally opaque portions of the HUD slides, with no road slide) was approximately 0.27 cd/m^2. The luminances of the road images are harder to characterize because they were photographs of complex real-world scenes. In order to provide information about the road-image luminances in the most crucial areas, the luminances of the projected road images at the positions where the map images were to appear were photometered from the subject's eye point using a 3-degree field of view (with the background lamp on, but no HUD slide). Those luminances ranged from 0.71 cd/m^2 to 66.0 cd/m^2, with a geometric mean of 13.0 cd/m^2.

Procedure

Subjects were run individually, each in a single session that took about an hour. Each subject was asked to sit in a chair facing the projection screen. The experimenter then read a short set of instructions that described automotive applications of HUDs and explained the tasks that the subject would be asked to perform. The experimenter showed the subject several example stimuli and then began a set of 180 trials.

Just before each trial, random access projectors were used to select the HUD slide and the road slide that would be paired on that trial. The experimenter indicated to the subject that the trial was about to take place by saying "ready," and then pushed a button that caused the shutters on the projectors to open for 30 ms.

On each trial the subject was required to perform two tasks. First, the subject had to say "right" or "left" to indicate the direction of the final turn that would need to be made according to the map represented on the HUD slide. For example, the correct answer for the map shown in the top, left panel of Figure 5 would be "left." The destination symbol in that panel is on the right side of that map (and therefore to the right from the point of view depicted by the arrow), but it would to the left of a driver who was approaching it after making the two turns necessary to approach it on the nearest adjoining road. Second, the subject had to say "yes" or "no" to indicate whether a pedestrian was present in the road slide. For both questions the two possible responses were correct equally often, and the correct response on each question was unrelated to the correct response on the other. The experimenter recorded the subject's responses and then prepared for the next trial. Each trial took about 15 seconds.

Subjects were told to do as well as possible on both tasks, but that they should favor the HUD task to the extent that there was conflict between the tasks. They were told to fixate the location at which the HUD was about to appear just before each stimulus presentation in order to get the best view of the HUD. They knew where to fixate because the HUD location was constant within blocks of 20 trials (as explained below), and the experimenter announced the upcoming HUD location before each block.

Design

There were 9 blocks of 20 trials in each session. Thus, each third of a session was made up of three blocks. Each of the three HUD positions was used in one of the three blocks in each third of the experiment. The order in which the HUD positions were used within each third was balanced within and across subjects according to a Latin square design. The orderings of the 20 trials within blocks were randomized individually for each subject.

The combination of the 120 HUD slides and the 12 road slides yields 1440 HUD-slide/road-slide pairs. This relatively large number of stimulus combinations was used in order to provide subjects with approximately the variety that they might normally encounter in driving. In order to keep the length of sessions manageable, individual subjects were shown sets of 180 pairs that were selected according to a split-plot design.

Results

Two analyses of variance were performed, one for error rates on the map task and one for error rates on the road task. The analyses were parallel in form; each included age and HUD location as factors.

The main effect of age was significant for both the HUD task, $F(1,22) = 9.08, p < .01$, and the pedestrian task, $F(1,22) = 11.63, p < .01$. Those effects are shown in Figure 6. As might be expected, younger subjects made fewer errors on both tasks.

The effect of the angle of the HUD below the horizon was also significant for both the HUD task, $F(2,44) = 4.85, p < .05$, and the pedestrian task, $F(2,44) = 72.08, p < .001$. Those results are shown in Figure 7. Although the effect of angle on the HUD task is statistically significant, it is small. That is consistent with the instructions that subjects received to emphasize accuracy on that task and to fixate the location of the HUD.

The interaction of age and HUD angle was not significant for the HUD task, $F(2,44) = 2.45, p > .05$, but was significant for the pedestrian task, $F(2,44) = 7.29, p < .01$. Those results are shown in Figures 8 and 9, respectively.

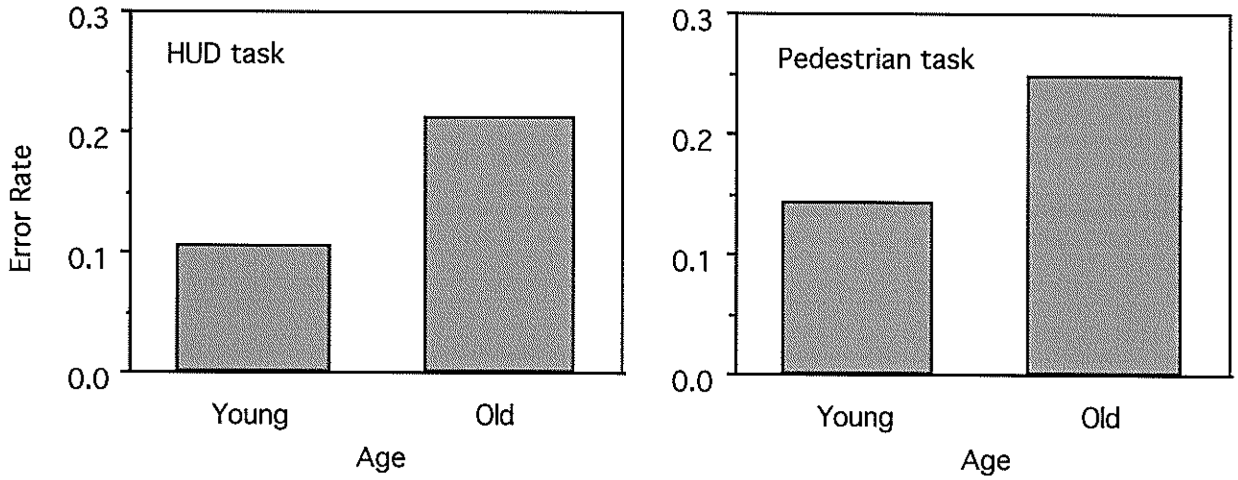

Figure 6. The main effect of age for errors on each of the two tasks.

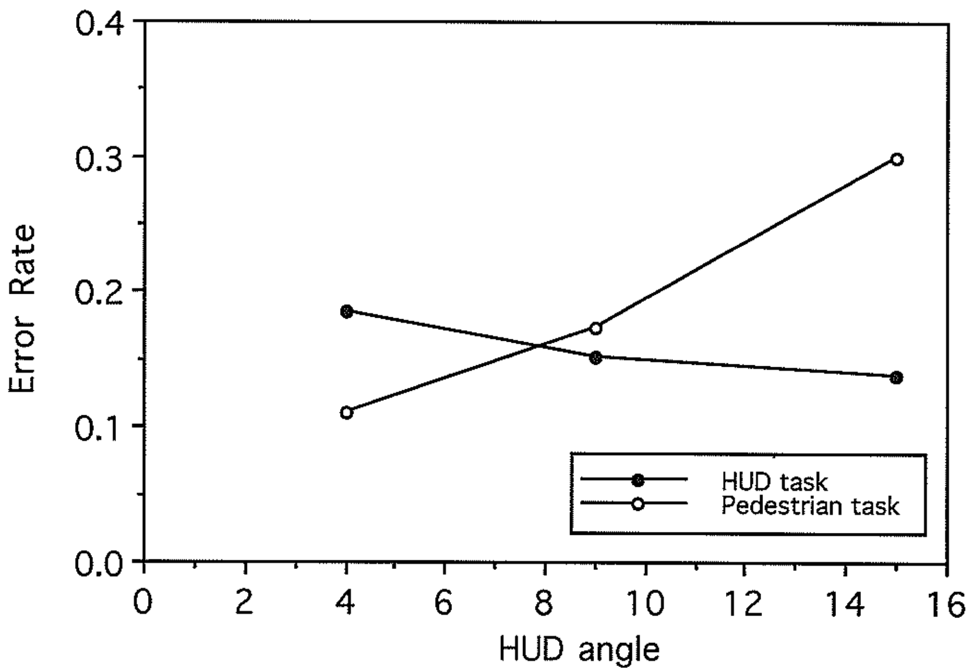

Figure 7. Error rates on both tasks as functions of the angle of the center of the HUD below the horizon.

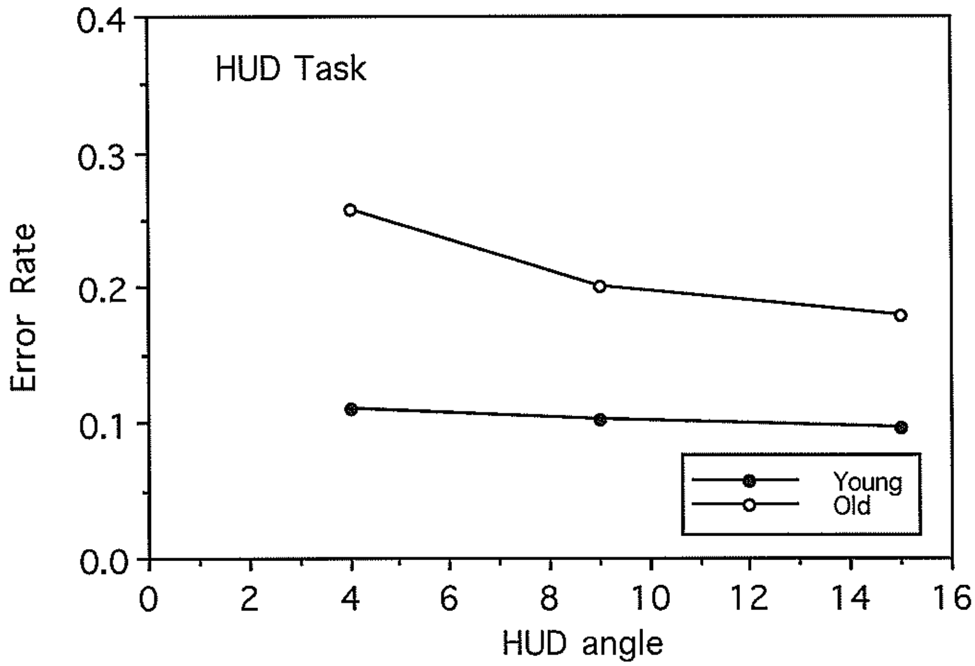

Figure 8. The interaction of age and HUD angle for error rates on the HUD task.

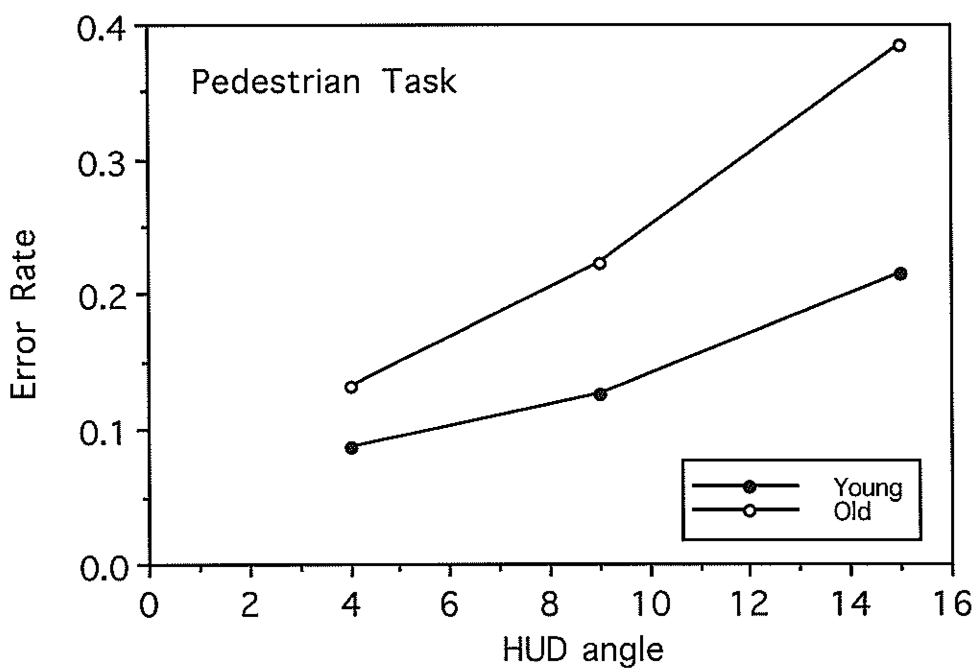

Figure 9. The interaction of age and HUD angle for error rates on the pedestrian task.

Discussion and Conclusions

These results demonstrate that the benefits that HUDs can provide in allowing drivers to maintain sensitivity to the road while monitoring a vehicle display continue to increase as the angular location of the HUD is brought closer to the direction of travel. For the stimuli and tasks used in this experiment, which are reasonably representative of the actual demands of driving, there seems to be no point at which the benefits of the HUD level off. The range of angular locations explored—15, 9, and 4 degrees—extends as close to the direction of travel as possible without causing the HUD to mask important road stimuli.

This study did not address the issue of how drivers' attention to displays in general affects the safety and efficiency of driving. For example, at variance with what is now common practice, some have argued that drivers should never look at cellular phone displays while driving. The results of this study should be interpreted as quantifying how location affects the benefits of HUDs for situations in which it is already assumed that a driver is attending to a display.

Older people performed differently from younger people in several ways. They made more mistakes overall on both the primary task (the HUD task) and the secondary task (the road task). Figure 8 shows that there was a tendency for them to have more trouble maintaining constant performance on the HUD task for different angles, although the interaction of age and angle was not significant. The age-by-angle interaction is very strong for the pedestrian task. This is consistent with the finding that older subjects have smaller UFOVs (Ball et al., 1990) because the divided-attention task that subjects performed in this experiment is formally very similar to the task used to define UFOV. Because older people have difficulty allocating attention to widely separated areas of their visual fields, the benefits of presenting information head-up, and the increase in those benefits as a HUD is brought closer to the direction of travel, should be greater for older than for younger drivers.

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