Effects of Superimposition of a Head-Up Display on Driving Performance and Glance Behavior in the Elderly

Hyung Jun Oh, Sang Min Ko & Yong Gu Ji

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A vehicle head-up display (HUD) has a semitransparent property that utilizes a method of projecting light onto the windshield. The semitransparent characteristic of the HUD generates continuous superimposition between the “HUD graphic” and “road environment events.” This study aims to determine the effects of HUD use on elderly driving. Two age groups (elderly, younger) performed tasks (speed monitoring, navigation) utilizing two types of display (HUD, head-down display) in two different circumstances (high superimposition level, low superimposition level). Subject performance was evaluated by having the subjects execute a secondary display task while performing a primary driving task with an eye-tracking task. In addition, the degree of driver visual distraction was verified through the measurement of display glance duration. The results showed that an increase in superimposition negatively affected driver glance duration independent of age. However, the use of HUD in low superimposition situations showed relative advantages with regard to display use independent of age. This study confirmed that the negative effects of HUD use need to be considered during the selection of HUD information and display location. In particular, this study verifies that special attention should be given to the negative effects of superimposition of text information for use by an elderly population.

1. INTRODUCTION

Humans use a multitude of senses to perceive external information. Among the various senses, sight is most commonly used for information reception, and most environmental information is perceived through sight (Jung & Kee, 1996, Masih-Tehrani & Janabi-Sharifi, 2008). Drivers also utilize sight to monitor information systems in vehicles. In particular, driving is a task in which visual aspects must be considered in the design of information systems (Owsley, 2011).

Existing studies have described factors of the visual aspects of driving for the design of information systems in vehicles. First, in-vehicle information systems (IVIS) should be designed for use in locations that ensure sufficient visibility for drivers to perceive road environments. A shorter distance between the driver front view and display information location may result in better visibility, resulting in positive effects on driving performance and response time of drivers (Wittmann et al., 2006). In addition, IVIS should be designed to minimize display glance duration. Because visual distraction and perception load increase when the display glance duration increases during driving (Bao, Kiss, & Wittmann, 2002; De Waard, 1996; Noy, Lemoine, Klachan, & Burns, 2004), systems should be designed to ensure that driver gaze is fixed to the front rather than on a display in order to assure safe driving.

Head-up displays (HUDs) comply with the aforementioned design guidelines for information systems in vehicles and are being increasingly in new vehicles. HUDs utilize the windshield area in front of the driver as a special display region. HUDs are characterized by a semitransparent display in which the light source is projected onto the windshield, providing drivers with information. Providing driving information in the front view has been shown to reduce display glance duration and has numerous advantages in driving performance, response speed, and workload.

The HUD has a semitransparent property that utilizes a method of projecting a light source onto the windshield. This semitransparent characteristic generates continuous superimposition between the “HUD graphic” and “road environment event” (Tangmanee & Teeravarunyou, 2012). The visual superimposition in HUD-utilized environments is a new characteristic that, to the best of our knowledge, has never before been implemented in the display of existing vehicles. This superimposition phenomenon could influence the visibility of icons and text in the display or be a driving distraction, resulting in an increase in display glance duration, thereby potentially impairing safe driving.

In particular, compared to other age groups the elderly might be more vulnerable to changes in information environments due to reduced cognitive and physical abilities. Elderly drivers are one of the most rapidly increasing age groups in terms of driving population and total driving distance. Thus, it is necessary to design IVIS that consider the driving abilities of elderly drivers. The HUD has not only the positive potential to increase
the amount of information available to the elderly in vehicles but also the potential for negative effects due to changes in the information environment.

Thus, the present study (a) verifies changes in HUD performance level and glance behavior in two age groups according to changes in the level of superimposition in HUD and (b) identifies differences in effects between age groups. In addition, to evaluate the usability of HUD for the elderly, this study (c) confirms differences in display performance level and glance behavior between HUD and head-down display (HDD) in each age group under different superimposition conditions.

2. LITERATURE REVIEW

2.1. HUD and Driver Behavior

Previously, comparative studies on HUD and HDD have been conducted mainly to determine the effects of HUD characteristics on driver behavior. Previous studies have experimented with response time and accuracy for risk factors or changes occurring outside vehicles, response time and accuracy with respect to display information in vehicles, and glance behavior while driving. A study by Liu and Wen (2004) determined the effects of utilization of two types of information displays (HUD, HDD) on driving performance level and psychological load in two different road conditions (high and low driving loads). Based on the result, HUD showed significantly faster driver response time to external information compared to HDD in a low driving load environment. HUD also showed better task performance in maintaining vehicle speed than did HDD. In addition, HUD involved less mental stress than HDD in a high driving load environment. Gish et al. (1999) conducted an experiment to determine the advantages and potential problems of HUD. In his study, task performance level was measured while drivers performed three tasks (speed monitoring, navigation, and warning detection) with respect to information in a vehicle provided via two types of displays (HDD and HUD). At the same time, Gish measured driver response performance level to events that occurred in the rearview mirror. To evaluate the effect of the display on task performance level, Gish conducted a test to determine whether drivers responded correctly to information in the display by controlling left and right buttons on a steering wheel. The results showed that HUD had a better overall response performance level to external events and showed an advantage in response to the warning detection task compared to HDD. A study by Sojourner and Antin (1990) verified that response time to a salient cue in a driving scene was faster when using HUD than when using a speedometer in a dashboard. A reduction in the checking glance time of drivers through the use of HUINTEGER has been verified in other studies as well (Bodziakowski & Allan, 1989; Kato et al., 1992; Sprenger, 1993). Previous studies have also reported that navigation error was lower in HUD compared to HDD (Burnett, 2003), and that road glance time increased with HUD compared to HDD (Kiefer, 1991). Existing studies have verified various characteristics that appear with the use of HUINTEGERs for younger drivers, but the effects of the use of HUINTEGER on elderly drivers have not yet been clearly determined.

2.2. Effect of Age on HUD Performance

The use of HUINTEGERs may have potentially positive effects on the driving behavior of the elderly. A study by Pauzie and Marin-Lamellet (1989) reported age-related increases in two driver behaviors in vehicles equipped with visual displays. First, the elderly showed an age-related increase in duration and frequency of glancing at a display. This indicates that elderly drivers showed a decrease in front glance duration while driving. Second, the amount of information that can be processed within a given time decreased as age increased. The advantages of HUINTEGERs such as a decrease in “display glance duration” and more rapid “response time to information” can thus result in positive effects in the elderly.

On the other hand, there may also be negative effects to using HUINTEGERs when driving because of the reduced physical abilities of the elderly. The visual superimposition effect that appears with HUINTEGER transparency requires greater driver attention. A study by Harrision et al. (1995) discussed HUINTEGER in terms of its fully transparent design and identified issues of focused, divided, and selective attention that are required when transparent displays are utilized. A user needs focused attention to concentrate on a single target object in the presence of a number of distracting stimulations that occur in the environment when a transparent display is utilized. In addition, users must be able to divide their attention among various surrounding stimuli while preserving attention on a single target object. A study by Shaheen and Niemeier (2001) determined five physical obstacles that may be experienced by the elderly due to increased age and suggested guidelines for vehicle design to overcome such obstacles. Shaheen’s study found that elderly drivers experience difficulties in discarding unnecessary surrounding information due to selective attention, resulting in difficulties in visual search. The reduced attention found in the elderly suggests that there may be other driving issues that are unique to elderly drivers using a transparent display.

The aforementioned literature review confirmed that the advantages of HUINTEGERs have the potential to help the elderly use vehicle information systems. On the other hand, potential negative effects inherent in the use of the HUINTEGER were determined as well. Existing studies have confirmed various characteristics of the use of HUINTEGERs among younger drivers, but the effects of using HUINTEGERs in elderly drivers have not yet been determined. The present study aims to verify the effects of HUINTEGERs on the elderly and the relative differences in display use between HUINTEGER and HDD depending on age.

3. METHODS

3.1. Apparatus

For this study, a simulated driving environment inside a vehicle was configured with a steering wheel and seats. The
steering wheel in this study was the Driving Force GT model from Logitech, and the control-related data from the wheel was transferred to a personal computer (PC) through a program implemented in Java. The transferred data were control direction of the steering wheel, button control direction, and control time information. The steering wheel was able to perform force feedback and wheel rotation at 90°, thereby providing a real driving sensation when steering left or right. During the driving simulation, downtown noise recorded in real driving situations was provided continuously through speakers. An actual seat from the Genesis model from Hyundai Motor was installed.

The experimental task was displayed on a 50-in. HDTV screen located 2 m in front of the driver. To measure glance behavior, SMI Eye Tracking Glasses 2.0 (SensoMotoric Instruments, Teltow, Germany), mobile eye-tracking glasses, were used. To analyze the measurement results, BeGaze software from SMI was used.

This study referred to previous studies in terms of the size, location, and specifications of the display. A full-color HUD currently available on the market was used in the present study. This model provides full-color light in the display screen with a 4.5-in. virtual image (9.9 × 5.5 cm), 400 × 240 resolution, and brightness control within the range of 3,100–26,000 cd/m. The HUD graphic shape was controlled remotely via PC. A study by Freeman (2011) outlined the general specifications required for HUD manufacture, and the HUD environment was created based on these guidelines. Light sources that created HUD images were projected through specially manufactured glass. The distance between the HUD image and the driver was set to 1.5 m, and the angle between them was set to 4° to 12° below the driver gaze.

The HDD was designed by referring to previous studies because manufacturers use different display sizes. A 9.7-in. LED tablet PC with 2,048 × 1,536 resolution was utilized for HDD. The HDD was controlled remotely via PC in order to control the display information. The HDD was arranged next to the air-conditioning and stereo control panel (Liu & Wen, 2004).

3.2. Stimuli

Driving scenes required for the experiment were edited in accordance with the study simulation levels after we filmed them using a camcorder. The shooting session was conducted in downtown driving situations between 1:00 p.m. and 3:00 p.m. in slightly overcast weather. The shooting session was conducted assuming general driving situations. The images were edited to be suitable for the stimulus level using Adobe Premiere software.

The superimposition phenomenon in the HUD occurs when the HUD graphics overlap with objects such as vehicles, buildings, and pedestrians. Thus, the stimulus level of shot images was determined by adjusting the number of objects in the HUD graphic area. Previous studies on driving extremely adjusted the number of units (i.e., buildings, cars, and pedestrians) on the road to control the stimulus level (Horberry, Anderson, Regan, Triggs, & Brown, 2006; Stinchcombe & Gagnon, 2010, 2013). This study also controlled the stimulus level based on this method and determined it by extremely adjusting the number of units in a HUD region.

An image with a high-stimulus level had more frequency of overlap between the “HUD graphics” and “objects” that appeared in the driving background, as shown in the left side of Figure 1. On the other hand, an image with a low stimulus level had a lower frequency of superimposition between the “HUD graphics” and “objects” in the driving background, as shown in the right side of Figure 1.

3.3. Task

A driver interacts with the primary driving functions, such as steering, accelerating, and braking. A driver also performs secondary tasks within the vehicle (Harvey, Stanton, Pickering, McDonald, & Zheng, 2011). This study utilized a dual-task methodology for confirming the efficiency of the display utilization. The task efficiency of the subjects was evaluated by having subjects perform a secondary display task while performing a primary driving task.

This study utilized a tracking task as the primary task in virtual driving situations. In the tracking task, the subjects were instructed to look to the front and perform controls similar to those in actual driving. The present study selected the primary task by modifying a tracking task used in a study by George, Boudreau, and Smiley (1997). In this task, a tracking

FIG. 1. Examples of a high-stimulus image (left) and a low-stimulus image (right).
box located in the center maintained its unstable state due to an arbitrary force applied to the sides. To correct sideways deviation, the subjects were required to continuously move the tracking box to the center (tracking target) utilizing the right and left steering wheel controls. The tracking task was programmed in Java, the distance from the center to the box’s center location was measured 10 times per second, and the results were sent to a PC.

The tracking task intends to assume primary task conditions of the driver. In this regard, it is merely a supplementary method to perform a secondary task by assuming driving conditions and not the main objective of analysis in this study.

The present study selected two secondary tasks. The first was a speed monitoring task requiring subjects to verify and respond to the current vehicle speed and the speed limit, and the second was a navigation task requiring subjects to verify and respond to navigation information (see Figure 2).

The secondary tasks were performed simultaneous to the primary task. The subjects concentrated on the primary task through the wheel control while looking forward. During performance of the primary task, prearranged specific events occurred. Shortly after an event, subjects were required to glance at the display to verify the information and push the steering wheel button according to the information received. One method for comparing display task performance between HUD and HDD was outlined in a study by Gish et al. (1999), which used left and right buttons on a steering wheel in response to information indicated on the display. In a study by Wittmann et al. (2006), a method to determine the performance level of a driver according to the display location in a vehicle was a secondary task where numeric information marked in the display was matched continuously with the right and left button control on the steering wheel.

The process for the speed monitoring task was as follows: During performance of the primary task, the driver glanced at the display to verify the current speed and the speed limit when an alarm sounded through speakers. If the current speed indicated on the left side of the display was higher than the speed limit marked on the right side, the left button on the steering wheel was pushed; otherwise, the right button was pushed. The process of the navigation task was as follows: Once the alarm sounded, subjects verified the direction of the navigation symbol marked on the display. According to this direction, subjects pushed the left or right button on the steering wheel.

3.4. Procedure

The experiment was divided into two groups according to secondary task. The subjects conducted the experiment under eight conditions: two types of secondary tasks (speed monitoring, navigation), two different display environments (HUD, HDD), and two different stimulus levels (high, low). These eight conditions were presented randomly to subjects to reduce errors caused by learning.

Prior to the experiment, the subjects had sufficient time to practice until they were familiar with the tasks. Because elderly subjects may have greater learning difficulties compared to the younger, a mandatory practice time longer than 20 min was provided to the subjects prior to the experiment.

The subjects continuously controlled the location of the tracking box via the steering wheel while concentrating on the primary task. Once an alarm sounded through speakers, the secondary task was performed with the left and right button controls on the steering wheel while performing the primary task. The subjects were instructed to pay the greatest attention to the primary task and to assume a real driving situation. In every individual test, 10 alarm sounds were generated. Each alarm was generated randomly within a range of 20 to 40 s. Each individual test required approximately 6 min, and a rest time of 5 min was imposed between individual tests. The experiment required an average of 2.5 hr.

3.5. Measurement

In the present study, two variables, performance level and glance behavior, were used as dependent variables with respect to the secondary driving task. Response time and accuracy were measured for the secondary task. Response time in the secondary task was defined as the time required by a subject from the occurrence of an alarm to the pushing of the steering wheel button. Accuracy was measured by the rate of correct responses to the secondary task.

When designing information systems for vehicles, especially visual displays, it is essential to consider visual distraction of drivers stemming from system use. Glance behavior has been used in various studies as an index for measuring distraction caused by visual displays in vehicles. A study by Zhang, Smith, and Witt (2006) confirmed the significance of glance behavior as a reliable index of visual distraction. The glance behavior index measured in existing studies on information displays in vehicles consists of two variables: glance duration at the display and number of glances. A study by Lin, Wu, and Chien (2010) measured glance behavior as a method for measuring visual distraction level according to information representation type in the vehicle display. A study by Chiang, Brooks, and Weir (2004) measured glance behavior as a method for observing driver behavior during a system input task during navigation according to road conditions. In addition, studies of vehicle displays, including HUDs, have also utilized glance behavior as an index for representing visual distraction during driving.
Glance duration in the present study was defined as the time spent by a subject glancing away from the primary task in order to perform the secondary task. During the primary task, tracking errors were measured. Tracking error refers to the standard deviation of subjects with respect to the distance between the tracking target located in the center and the tracking box during task performance (George, Boudreau, & Smiley, 1997).

3.6. Participants
The experiment in the present study involved two subject groups, 12 elderly subjects older than 65 years of age (10 male, two female) and 13 younger subjects (11 male, two female). The mean age of the elderly subjects was 69.5 years (SD = 3.5). Elderly subjects drove more than 5 hr per week. The mean visual acuity of the elderly was 0.97 (SD = 0.24) for the left eye and 0.95 (SD = 0.28) for the right eye. The mean age of the 13 younger subjects was 28.2 years (SD = 2.7). Younger subjects also drove more than 5 hr per week. The mean visual acuity for the younger subjects was 0.89 (SD = 0.38) for the left eye and 1.00 (SD = 0.37) for the right eye. The subjects were limited to those who could verify information in the display and immediately respond to the information by controlling the steering wheel. Approximately $50 was paid to each of the participants.

4. RESULTS
To determine the effect of changes in stimulus level on HUD use, (a) differences in measurements in HUDs according to changes in stimulus level were analyzed by t-test. Then, to determine differences in the effect of changes in stimulus levels on measurements by age, (b) a univariate analysis was conducted between age and stimuli. Because the changes in stimulus levels in HDDs caused by the location of the display did not influence measurement, HDD was excluded from the preceding analyses. The actual measurements of HDD also showed no significant differences according to the level of superimposition. Finally, (c) differences in measurements according to display (HUD, HDD) in the same stimulus condition were analyzed by t-test.

4.1. Speed Monitoring Task
HUD comparison under different stimuli. For the younger, there was a significant difference in glance duration as the level of stimulus changed. At a higher stimulus level, glance duration was 212 ms longer than for the lower stimulus level (p = .000). For the younger, response times did not show any significant differences (p = .082) according to stimulus level, and the accuracy of task execution also had no significant differences (p = .540).

For the elderly, all measurements changed significantly according to stimulus level. The response time of the elderly was 183 ms longer for the higher stimulus level than for the lower stimulus level (p = .000). The accuracy of task execution was reduced by 10.83% in the higher stimulus level compared to the lower stimulus level (p = .028). Glance duration of the elderly was 353 ms longer for the higher stimulus level than for the lower stimulus level (p = .000; see Table 1).

Differences between stimulus effects. The interaction between stimulus level and age showed that response time (F = 4.727, p = .030) and accuracy (F = 4.420, p = .041) were significantly different (see Table 2). In the present study, stimulus level change had a greater effect on response time and HUD accuracy in the elderly than in the younger (see Figure 3). With respect to glance duration (F = 2.518, p = .114), no significant differences caused by the interaction between age and stimulus level were found.

Comparison of HUD and HDD under the same stimuli. The younger showed significant differences in response time and glance duration according to display differences in the low stimulus level. The younger had a 103 ms faster task execution time when using HUD compared to using HDD (p = .007; see Table 3). Glance duration in HUD was also reduced by 377 ms.
TABLE 2
Analysis of Variance Significance Values for Interaction Between Age and Stimulus (Speed Monitoring Task)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Response Time</th>
<th>Accuracy</th>
<th>Glance Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age × Stimuli</td>
<td>0.030*</td>
<td>0.041*</td>
<td>0.114</td>
</tr>
</tbody>
</table>

*p < .05.

FIG. 3. Effects of stimulus and age on reaction time, accuracy, and glance duration during the speed monitoring task.

TABLE 3
Performance Across Stimuli Conditions With Different Display for Younger (Speed Monitoring Task)

<table>
<thead>
<tr>
<th>Display</th>
<th>Stimulus</th>
<th>Measurement</th>
<th>HUD</th>
<th>HDD</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Response time (ms)</td>
<td>1686</td>
<td>1789</td>
<td>−2.745</td>
<td>.007**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy (%)</td>
<td>98.46</td>
<td>95.38</td>
<td>1.163</td>
<td>.256</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glance duration (ms)</td>
<td>646</td>
<td>1023</td>
<td>−7.984</td>
<td>.000***</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Response time (ms)</td>
<td>1757</td>
<td>1787</td>
<td>−.741</td>
<td>.459</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy (%)</td>
<td>97.41</td>
<td>95.3</td>
<td>1.050</td>
<td>.305</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glance duration (ms)</td>
<td>898</td>
<td>955</td>
<td>−1.011</td>
<td>.314</td>
</tr>
</tbody>
</table>

Note. HUD = head-up display; HDD = head-down display.

**p < .01. ***p < .001.

compared to that of HDD (p = .000). For the younger, task execution accuracy showed no significant difference between displays (p = .256).

For the younger, no significant differences were found with regard to response time (p = .459), accuracy (p = .305), or display glance time (p = .314) according to display difference when performing the secondary task under the high-stimulus level.

The elderly showed a significant difference in response time (p = .004) and glance duration (p = .000) between displays when performing the secondary task in the low-stimulus level (see Table 4). The elderly performed the task 142 ms faster with HUD compared to HDD, and the display glance time was reduced by 433 ms with HUD compared to HDD. There was no significant difference in the accuracy of the secondary task execution (p = .135).

The elderly showed significant differences in response time (p = .001) and accuracy (p = .012) between the two displays when performing the secondary task in the high stimulus level. The elderly performed the secondary task 157 ms slower with HUD compared to HDD, and accuracy was reduced by 12.59% for HUD compared to HDD. There was no significant difference in glance duration according to display (p = .799).

4.2. Navigation Task

HUD comparison under different stimuli. For the younger, there was a significant difference in glance duration as the stimulus level changed (see Table 5). Glance duration for the elderly
TABLE 4
Performance Across Stimuli Conditions With Different Display for Elderly (Speed Monitoring Task)

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Measurement</th>
<th>HUD</th>
<th>HDD</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Response time (ms)</td>
<td>1968</td>
<td>2110</td>
<td>−2.912</td>
<td>.004**</td>
</tr>
<tr>
<td></td>
<td>Accuracy (%)</td>
<td>96.57</td>
<td>92.5</td>
<td>1.554</td>
<td>.135</td>
</tr>
<tr>
<td></td>
<td>Glance duration (ms)</td>
<td>924</td>
<td>1357</td>
<td>−11.925</td>
<td>.000**</td>
</tr>
<tr>
<td>Low</td>
<td>Response time (ms)</td>
<td>2169</td>
<td>2012</td>
<td>3.493</td>
<td>.001**</td>
</tr>
<tr>
<td></td>
<td>Accuracy (%)</td>
<td>85.74</td>
<td>98.33</td>
<td>−2.923</td>
<td>.012*</td>
</tr>
<tr>
<td></td>
<td>Glance duration (ms)</td>
<td>1277</td>
<td>1287</td>
<td>−0.255</td>
<td>.799</td>
</tr>
</tbody>
</table>

Note. HUD = head-up display; HDD = head-down display.
*p < .05. **p < .01.

Differences between stimulus effects. The analysis of the interaction between stimulus level and age showed that the differences in response time (F = 0.458, p = 0.499) and accuracy (F = 0.873, p = 0.355) were not significant (see Table 6). On the other hand, there was a significant difference in glance duration (F = 4.195, p = 0.041) due to the interaction between age and stimulus level. These results indicate that stimulus level changes have a greater effect on glance duration in HUD among the elderly than the younger (see Figure 4).

HUD and HDD comparison under the same stimuli. For the younger, there were significant differences in response time (p = .028) and display glance time (p = .000) according to display type at the low stimulus level (see Table 7). It was found that the younger performed the secondary task 72 ms faster with HUD compared to HDD, and display glance time was reduced by 358 ms. There was no significant difference in the accuracy of secondary task execution according to display type.

For the younger, there were significant differences in response time (p = .020) and display glance time (p = .000) according to display type at the high stimulus level. It was found that the younger performed the secondary task 82 ms faster with HUD compared to HDD, and the display glance time was reduced by 316 ms. There was no significant difference in accuracy according to display type (p = .616).

Elderly subjects showed a significant difference in glance duration according to display type for the low stimulus level (see Table 8). Display glance time was reduced by 543 ms with HUD compared to HDD (p = .000). For the younger, response time showed no significant difference (p = .554) according to stimulus level, and accuracy of task execution also showed no significant difference (p = .167).

For the elderly, there was a significant difference in display glance time according to display type in the high stimulus condition. The display glance time was reduced by 296 ms with HUD compared to HDD (p = .000). For the elderly, response
TABLE 6
Analysis of Variance Significance Values for Interaction Between Age and Stimulus (Navigation Task)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Response Time</th>
<th>Accuracy</th>
<th>Glance Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age × Stimuli</td>
<td>0.499</td>
<td>0.355</td>
<td>0.041*</td>
</tr>
</tbody>
</table>

*p < .05.

FIG. 4. Effects of stimulus and age on reaction time, accuracy, and glance duration during the navigation task.

TABLE 7
Performance Across Stimuli Conditions With Different Display for Younger (Navigation Task)

<table>
<thead>
<tr>
<th>Display</th>
<th>Stimulus</th>
<th>Measurement</th>
<th>HUD</th>
<th>HDD</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Response time (ms)</td>
<td>1551</td>
<td>1623</td>
<td>−2.204</td>
<td>.028*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy (%)</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glance duration (ms)</td>
<td>437</td>
<td>795</td>
<td>−9.103</td>
<td>.000***</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Response time (ms)</td>
<td>1520</td>
<td>1602</td>
<td>−2.942</td>
<td>.020*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy (%)</td>
<td>99.15</td>
<td>98.46</td>
<td>0.507</td>
<td>.616</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glance duration (ms)</td>
<td>561</td>
<td>877</td>
<td>−6.550</td>
<td>.000***</td>
</tr>
</tbody>
</table>

Note. HUD = head-up display; HDD = head-down display.  
*p < .05. ***p < .001.

TABLE 8
Performance Across Stimuli Conditions with Different Display for Elderly (Navigation Task)

<table>
<thead>
<tr>
<th>Display</th>
<th>Stimulus</th>
<th>Measurement</th>
<th>HUD</th>
<th>HDD</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Response time (ms)</td>
<td>1657</td>
<td>1680</td>
<td>−0.592</td>
<td>.554</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy (%)</td>
<td>98.24</td>
<td>100</td>
<td>−1.481</td>
<td>.167</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glance duration (ms)</td>
<td>478</td>
<td>1021</td>
<td>−16.706</td>
<td>.000***</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Response time (ms)</td>
<td>1659</td>
<td>1757</td>
<td>−1.493</td>
<td>.137</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy (%)</td>
<td>94.07</td>
<td>95</td>
<td>−.194</td>
<td>.848</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glance duration (ms)</td>
<td>717</td>
<td>1013</td>
<td>−7.532</td>
<td>.000***</td>
</tr>
</tbody>
</table>

Note. HUD = head-up display; HHD = head-down display.  
***p < .001.
times showed no significant difference ($p = .137$) according to display type, and task execution accuracy also showed no significant difference ($p = .848$).

### 4.3. Tracking Task

To determine tracking error differences according to individual conditions, an analysis of variance was conducted on mean values of tracking errors of subjects measured under the eight conditions. The secondary task is instantly performed at a certain period during the tracking task, so it does not affect the entire tracking task performance. Because the performance of the tracking task varies according to age, analysis was performed by dividing age, and the analytic result was used to supplement secondary task data.

For the elderly, there was no significant difference in mean tracking error between individual conditions ($F = 0.655$, $p = .709$), and no significant difference between groups was found in the post-test using Tukey’s honestly significant difference (see Figure 5).

For the younger, there was no significant difference in mean tracking error between individual conditions ($F = 1.497$, $p = .178$), and no significant difference between groups was found in the post-test using Tukey’s honestly significant difference (see Figure 6).

### 5. CONCLUSION

This study verified that the superimposition of road environment and display when using HUD had a negative effect on display glance time with a high superimposition level regardless of age. In addition, an increase in glance duration, required to verify information under a high superimposition level in HUD use, was found for all ages and tasks. Because changes caused by display superimposition affect HUD glance duration independent of age and task, drivers should use caution in superimposition situations to reduce display glance time.

Elderly subjects responded more sensitively to changes in superimposition level than do the younger when speed information was verified through HUD. The elderly were more greatly affected by superimposition in HUD than were the younger with respect to response time and accuracy. This means that the elderly responded more sensitively to changes in superimposition level with respect to time and accuracy as they verified information through the HUD. Thus, the present study suggests that the elderly should use caution in superimposition situations when verifying information through an HUD.

In addition, when the elderly verified speed information through the HUD, an increase in superimposition level negatively affected performance level and glance duration (response time = 0.18 s, accuracy = 10.8%, display glance time = 0.35 s).

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**FIG. 5.** Tracking task errors for elderly (speed monitoring task, navigation task).

**FIG. 6.** Tracking task errors for younger (speed monitoring task, navigation task).
Negative effects on elderly subjects were also found in the relative comparison with HDD. For example, for the high superimposition level, the elderly showed no advantages in glance time when using HUD, although some advantage was found when using HDD. Rather, HDD showed better performance results in terms of response time and glance time compared to HUD. Therefore, an HDD may be preferable to HUD for elderly drivers when text information such as speed information must be viewed in situations with a high superimposition level.

For the low superimposition situation, the use of HUD had relative advantages compared to the use of HDD, independent of age. For the low superimposition situation, both age groups showed positive results in terms of response time and display glance time for display information in all tasks. In particular, display glance time for HUD was improved by 0.43 s during the speed monitoring task execution and 0.54 s during the navigation task execution. Considering the ISO 15005 (ISO 15005, 2002) recommendation that driver glance duration for IVIS should be shorter than 1.5 s, the use of HUD at a low superimposition level has considerable advantages in glance time over the use of HDD. Thus, if HUD is utilized in consideration of the superimposition phenomenon, display glance duration would be reduced independent of age, thereby increasing driving safety.

Although negative effects with the use of HUD with an increase in superimposition level were verified when subjects were tasked with confirming the direction of symbolic information such as that used in navigation, the use of HUD had relative advantages over the use of HDD, independent of superimposition level. Although this study did not verify that symbolic information is less affected by the superimposition effect than text information, at a minimum, no weakness of HUDs with regard to text information was observed for verification of navigation direction.

This study found that the superimposition that occurs due to the display characteristics of HUDs can have a negative effect on drivers. In particular, when text information is displayed, problems that may occur due to superimposition can have negative effects on elderly subjects, demonstrating the need for careful design of text information displays for the elderly. Elderly drivers experience difficulties when driving and utilizing information in a vehicle because of reduced physical and cognitive abilities. The HUD is a fully transparent display and comprehensive attention resources combining focused, divided, and selective attention are required to use this display (Harrison et al., 1995). The elderly might face a problem in using the HUD in a certain condition because of their decreased cognitive ability. When using the HUD in a high superimposition condition, the elderly would lack cognitive resources, which can lead to an accident (Anstey, Wood, Lord, & Walker, 2005). They can also be affected by the decreased sensory ability related to driving while using the HUD. Depth perception plays an important role in the selection of appropriate information among superimposed information, such as that of the HUD (Margolis et al., 2002). However, decreased depth perception ability observed in the elderly can lead to an accident during driving, as well as a problem when using the HUD in a high superimposition condition. However, if such problems can be overcome with the aid of in-vehicle display designs that include HUD, elderly drivers may receive significant benefits (Dingus et al., 1997; Kirasic, 2000).

During the last few years, drivers have greatly benefited from new vehicular technologies (Lee, Forlizzi, Hudson, & Jun, 2015). Thus, automobile manufacturers are expanding on the existing basic types of HUDs for future automobile technology, proposing a full windshield HUD utilizing augmented reality, along with various changes in information type and location. Under these circumstances, the superimposition effect may become more significant. Therefore, HUD design should consider the negative effects of superimposition with various types of information and information display locations.

In the present study, the effects of display superimposition on drivers were verified, but an optimal method or display location to overcome these superimposition problems was not determined. When using the HUD, complexity of the background affects readability, and for this reason, HUD positioning is crucial (Ward, Parkes, & Crone, 1995). Particularly, this study verified that such complexity leads to more significant effects, thereby emphasizing the importance of HUD positioning. Further studies are needed to optimize the selection of HUD location to maximize usability and minimize the superimposition phenomenon. Although this study found differences in the effects of superimposition according to information type in HUD, it did not clearly verify the degree of effects according to information type. Future studies should include various types of information displayed in a vehicle HUD and determine their relative advantages, independent of superimposition level. Problems of the HUD that might generate due to visual factors can be compensated by using other cognitive elements. In particular, auditory modality and enhanced auditory cues are helpful in using IVIS more efficiently (Jeon et al., 2015). Furthermore, tactile warning also increases the secondary task performance of the driver (Scott & Gray, 2008). In addition, information can be transferred more accurately by using vibration, which is thus regarded as a good alternative to reduce interruption of the driver’s driving task (Cao, Van Der Sluis, Theune, & Nijholt, 2010). It is expected that more effective IVIS will be designed by applying various cognitive elements, such as auditory and tactile elements.

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