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Ergonomics Studies on Non-Traditional In-Vehicle Displays for Reducing Information Access Costs

정보 접근 비용 감소를 위한 비전통적 차량 내 디스플레이의 인간공학 연구

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Abstract

Ergonomics Studies on Non-Traditional In-Vehicle Displays for Reducing Information Access Costs

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Drivers should keep their eyes forward most of the time during driving to be in full control of the vehicle and to be aware of the dynamic road scene. Thus, it is important to locate in-vehicle displays showing information required for a series of driving tasks close to the driver's forward line-of-sight, and therefore, to reduce the eyes-off-the-road time. Automotive head-up display (HUD) system and camera monitor system (CMS) are promising non-traditional in-vehicle display systems that can reduce information access costs. HUD presents various information items directly on the driver's forward field of view, and allows the drivers to acquire necessary information while looking at the road ahead. CMS consists of cameras capturing vehicle's side and rear views and in-vehicle electronic displays presenting the real-time visual information, allowing the driver to obtain it inside a vehicle.

Despite the potential benefits and promising applications of HUD system

and CMS, however, there are some important research questions to be addressed for their ergonomics design. As for HUD system, presenting many information items indiscriminately can cause undesirable consequences, such as information overload, visual clutter and cognitive capture. Thus, only the necessary and important information must be selected and adequately presented according to the driving situation at hand. As for CMS, the electronic displays can be placed at any positions inside a vehicle and this flexibility in display layout design may be leveraged to develop systems that facilitate the driver's information processing, and also, alleviate the physical demands associated with checking side and rear views.

Therefore, the following ergonomics research questions were considered: 1) 'Among various information items displayed by the existing HUD systems, which ones are important?', 2) 'How should the important HUD information items be presented according to the driving situation?', 3) 'What are the design characteristics of CMS display layouts that can facilitate driver information processing?', and 4) 'What are the design characteristics of CMS display layouts that can reduce physical demands of driving?' As an effort to address some key knowledge gaps regarding these research questions and contribute to the ergonomics design of these non-traditional in-vehicle display systems, two major studies were conducted – one on HUD information items, and the other on CMS display layouts.

In the study on HUD information items, a user survey was conducted to 1) determine the perceived importance of twenty-two information items displayed by the existing commercial automotive HUD systems, and to 2) examine the contexts of use and the user-perceived design improvement points for high-priority HUD information items. A total of fifty-one drivers with significant prior HUD use

experience participated. For each information item, the participants subjectively evaluated its importance, and described its contexts of use and design improvement points. The information items varied greatly in perceived importance, and current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status, and low fuel warning were of highest importance. For eleven high-priority information items, design implications and future research directions for the ergonomics design of HUD systems were derived.

In the study on CMS display layouts, a driving simulator experiment was conducted to comparatively evaluate three CMS display layouts with the traditional side-view mirror arrangement in terms of 1) driver information processing and 2) physical demands of driving. The three layouts placed two side-view displays inside the car nearby the conventional side-view mirrors, on the dashboard at each side of the steering wheel, and on the center fascia with the displays joined side-by-side, respectively. Twenty-two participants performed a safety-critical lane changing task with each layout design. Compared to the traditional mirror system, all three CMS display layouts facilitated information processing and reduced physical demands. Design characteristics leading to such beneficial effects were placing CMS displays close to the normal line-of-sight to reduce eye gaze travel distance and locating each CMS display on each side of the driver to maintain compatibility.

Keywords: head up display (HUD), experienced users, importance of information items, contexts of information use, design improvement points, camera monitor system (CMS), in-vehicle side-view displays, display layout, information processing, physical demands
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Chapter 1

Introduction

1.1 Research Background

Up to 90% of the information necessary to flawlessly accomplish the task of driving is perceived by the visual channel (Plavšic et al. 2009). Since vision is the primary source of information available to drivers, efficient processing of visual information is essential to driving (ISO 15007-1:2014). Basically, for a driver to be in full control of the vehicle and be aware of the dynamic road scene, the driver's gaze should be directed towards the road scene (Stevens et al. 2002).

While mostly keeping their eyes forward during driving, drivers sometimes need to look at in-vehicle displays to acquire information needed for a series of driving tasks. The time spent making eye and head movements and looking at the in-vehicle displays is the time not spent looking at the road, or eyes-off-the-road time (Green et al. 1994). The eyes-off-the-road time consists of 1) the transition time of gaze shifting from the road to a display and then back to the road, and 2) the dwell time of gaze fixated on the display until the required information is encoded by human information processing (ISO 15007-1:2014; Schwalk, Hetzinger and Maier 2014). Both transition time and dwell time can be reduced through adequate spatial arrangement and ergonomic design of automotive displays, resulting in enhanced driving performance and safety. Especially, locating in-vehicle displays close to the driver's normal line-of-sight can reduce the transition time, and thereby, the eyes-off-the-road time. Indeed, numerous previous literatures have highlighted the importance of placing in-vehicle displays showing high-priority information (in terms of relevance to driving, criticality, urgency and frequency of use) close to the driver's normal line-of-sight to reduce the total eyes-off-the-road time (Green et al. 1994; Stevens et al. 2002; ISO/TR 16352:2005; Bhise 2011; SAE J2831 2012; Schwalk, Hetzinger and Maier 2014). Such positioning is also beneficial in that it allows a driver to use peripheral vision to monitor the road scene, maintain vehicle control, and detect emergencies even when principally viewing the displays (Stevens et al. 2002; Wittmann et al. 2006).

Automotive head-up display system and camera monitor system are promising non-traditional in-vehicle display systems that can reduce information access costs by presenting the necessary information closer to the driver's line-of-sight than the traditional systems, and thus, help enhance driving performance, safety, and comfort. Their basic concepts and advantages over the traditional systems are as follows:

Conventional in-vehicle displays located in the dashboard area require the drivers to lower their gaze to access information, and, thus, divert attention away from the road scene ahead – these displays are called head-down displays (HDD). In contrast to HDD, head-up display (HUD) presents various information directly onto the driver's forward field of view (FFOV) and allows the drivers to obtain the required information while keeping their eyes forward, without lowering their gazes away from the road ahead (Ward and Parkes 1994; Stevens et al. 2002; Liu 2003; Liu and Wen 2004; ISO/TR 16352:2005; Doshi, Cheng and Trivedi 2009; Wickens et al. 2013). Well-designed HUD is believed to provide advantages over HDD, including 1) less gaze and focal transition between the road scene and displays, 2) less eyes-off-the-road and re-accommodation times, and, possibly, 3) faster detection of displayed information and outside events. Such advantages are thought to have the potential to address the shortcomings of the conventional HDD system, and, thereby, help improve driving performance and safety (Sojourner and Antin 1990; Ward and Parkes 1994; Gish and Staplin 1995; Liu 2003; Liu and Wen 2004).

Major car manufacturers have shown great interest in replacing the traditional automotive mirrors with camera monitor system (CMS) (Alliance of Automobile Manufacturers and Tesla Motors, Inc. 2014). The basic concept of mirror-replacement by CMS is that compact cameras capture the driving events behind and beside the vehicle and in-vehicle electronic displays present the real-time visual information transmitted from the cameras (Terzis 2016). Thus, CMS side-view displays allow the drivers to acquire vehicle's side and rear views inside the vehicle, instead of turning their gazes towards the traditional exterior side-view mirrors. The idea of CMS has existed for decades and has been realized in some concept cars including Volkswagen XL1 (Lassa 2011). Currently, International Standard ISO 16505:2015 permits CMS to replace conventional mandatory automotive mirrors along with the latest version of United Nations Regulation No. 46 (Esser 2016; Terzis 2016). A CMS is known to offer advantages over the traditional mirror system, which include: 1) reduced aerodynamic drag and enhanced fuel efficiency by the elimination of exterior mirrors, 2) visual field expansion and blind spot elimination through the use of wide-angle camera lenses, and 3) improved vision for driving in adverse environments enabled by image processing and augmented reality (AR) visualization (Fornell Fagerström and Gårdlund 2012; Mohamed Ali and Fatin Bazilah 2014; Othmer 2014; Large et al. 2016; Schmidt et al. 2016; Smith et al. 2016; Terzis 2016).

Besides the common advantage of reducing information access costs, automotive HUDs and CMS displays could inherently increase screen estate for information presentation, complementing the already contested traditional dashboard with continuous development/introduction of advanced driver assistance systems (ADAS) and in-vehicle information systems (IVIS) (Ward and Parkes 1994; Charissis and Papanastasiou 2010). Thus, these two non-traditional in-vehicle displays could be harnessed as extra displays for providing further new/useful information to enhance driving performance, safety, and comfort.

1.2 Research Questions

Despite the abovementioned potential benefits and promising applications of HUD system and CMS, however, there are some important research questions to be addressed in order for these non-traditional in-vehicle display systems to be designed to best serve the driver as follows.

1.2.1 Research Questions for HUD system

Automotive HUD systems are becoming increasingly powerful leveraging the recent technological advances; some existing systems are capable of displaying multiple static and dynamic images at various locations throughout the entire driver's FFOV (Ward and Parkes 1994; Plavšic et al. 2009; Park et al. 2013; Guo et al. 2014; Broy et al. 2015). Such capability provides a platform on which plenty of useful applications can be developed (Plavšic et al. 2009; Rao et al. 2014; Kim et al. 2016). However, presenting many information items indiscriminately on HUD can cause undesirable consequences, such as information overload, visual clutter and cognitive capture, which can adversely affect driving performance and safety (Ward and Parkes 1994; Gish and Staplin 1995; Tufano 1997; Guo et al. 2014; Tippey, Sivaraj and Ferris 2017). To minimize such negative consequences, only the necessary and important information must be selected and adequately presented according to the driving situation at hand (Park, Kim and Chong 2012). Thus, important ergonomics research questions concerning the HUD information items are as follows:

Research question 1: Among various information items displayed by the existing HUD systems, which ones are important?

Research question 2: How should the important HUD information items be presented according to the driving situation?

1.2.2 Research Questions for CMS

Another important advantage of CMS over the traditional mirror system is that the electronic displays can be placed at any positions inside a vehicle other than the traditional mirrors positions. This flexibility in display layout design offers an opportunity for possible ergonomics design innovations/improvements. Since spatial arrangement of in-vehicle displays affects the driver's visual information processing (Bhise 2011), the CMS displays placed at desirable locations may facilitate driver information processing, and, thus, improve driving performance and safety. Aside from facilitating driver information processing, a CMS display layout may also be designed to alleviate the physical task demands associated with checking side and rear views, which may result in better driving comfort than the traditional mirror system. Thus, important ergonomics research questions concerning the CMS display layouts include the following:

Research question 3: What are the design characteristics of CMS display layouts that can facilitate driver information processing?

Research question 4: What are the design characteristics of CMS display layouts that can reduce physical demands of driving?

1.3 Dissertation Outline

This dissertation consists of two major studies in relation to the four research questions presented in Chapter 1.2 – one on HUD information items, and the other on CMS display layouts. In the study on HUD information items, various HUD information items' importance, usage contexts and design improvement points were examined. In the study on CMS display layouts, the effects of CMS side-view display layout design on the driver information processing and the physical demands of driving were investigated. The overall structure of this dissertation takes the form of five chapters (Figure 1.1). Brief descriptions of the chapters are presented below.

In Chapter 1, research background and research questions were described. The overall organization of this dissertation is also presented.

In Chapter 2, for each of the four research questions presented in Chapter 1.2, previous research efforts were reviewed and some key knowledge gaps were identified. Then, the research objectives to address such knowledge gaps were described.

Chapter 3 is concerned with the study on HUD information items. Research methods to achieve the research objectives for HUD information items were described in Chapter 3.1. In Chapter 3.2, the perceived importance of various HUD information items displayed by the existing HUD systems was determined. In Chapter 3.3, the contexts of use and user-perceived design improvement points for high-priority HUD information items were examined. In Chapter 3.4, concluding remarks and possible future research directions of this survey study on HUD information items were described.

Chapter 4 deals with study on CMS display layout. In Chapter 4.1, research methods to accomplish the research objectives for CMS display layout were presented. In Chapter 4.2, the effects of CMS side-view display layout design on the driver information processing were investigated. In Chapter 4.3, the impacts of CMS side-view display layout design on the physical demands of driving were examined. In Chapter 4.4, concluding remarks and some future research directions of this driving simulator study on CMS display layouts were described.

Finally, a brief summary and implications of the study were presented in Chapter 5, along with some future research ideas.

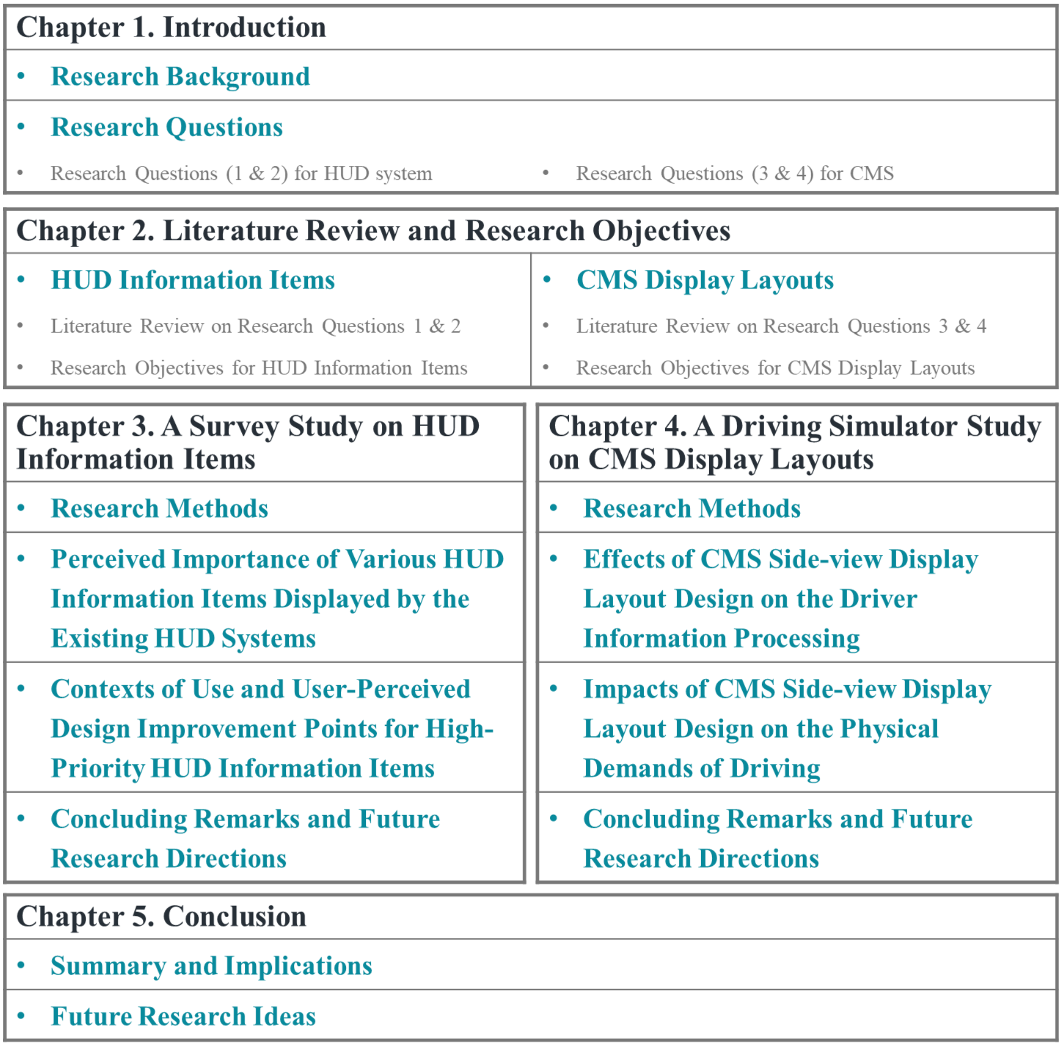

Figure 1.1: The overall structure of the dissertation

Chapter 2

Literature Review and Research Objectives

2.1 HUD Information Items

2.1.1 Literature Review on Research Question 1 (Among various information items displayed by the existing HUD systems, which ones are important?)

Despite the long history of automotive HUD systems and their increasing importance in the human-vehicle interface design, a question still remains about what they should display to best serve the driver. In determining the necessary and important information items to be presented on the HUD systems, it would be crucial to understand the user's information needs (Ward and Parkes 1994; Plavšic et al. 2009; Guo et al. 2014).

Several studies have been conducted to determine the automotive HUD users' information needs. Moon and Park (1998) determined the preference priority of nine HUD information items through a user survey. The priority order was, from highest to lowest, low fuel warning, engine overheat warning, turn signal indicators, battery warning, brake warning, speed, door open warning, seat belt warning, and hazard warning. Bergman (2011) conducted a survey study where seven participants drove their own cars with a prototype HUD system in real traffic for four days; the features found to be necessary for the HUD system were system warnings, GPS information, speeding indication, traffic/road condition information, traffic camera/police warnings, turn indicators, radio information, and temperature information. Park, Kim and Chong (2012) determined the perceived importance of HUD information items displayed by existing HUD systems through a survey; current speed, gear position, fuel status, and speed limit were found to be the high-importance items. Huang et al. (2013) conducted a questionnaire survey on the importance of different driving information items; speed-related information items, such as current speed and speed limit, were identified as the items of high importance. Guo et al. (2014) conducted a survey with 539 drivers on driver preference on HUD information items. Driving speed, relative speed and distance to the leading car, and traffic condition were identified as the most necessary elements.

Despite the previous research efforts above, however, the available knowledge on the driver's information needs for automotive HUD systems seems still limited. Two limitations of the existing research studies are as follows: first, the existing studies mostly surveyed drivers without enough prior experience of using HUD systems. The authors are not aware of any previous studies that examined a large sample of experienced automotive HUD system users. While inexperienced users can certainly offer meaningful information, it is reasonable to think that experienced users provide the most relevant insights regarding the user's information needs based on their actual long-term use experience. Second, each of the previous studies examined only a small subset of various information items that automotive HUD systems currently display. Evaluating a large set of information items within one study, which covers most of what were intended for automotive HUD systems, is needed to gain a complete picture of the relative significance of the relevant information items and accurately characterize the HUD users' information needs.

2.1.2 Literature Review on Research Question 2: (How should the important HUD information items be presented according to the driving situation?)

Even after three decades of automotive HUD use and related research efforts, the question of how to design the automotive HUD system to best serve the driver still remains an on-going research challenge. As in other man-made systems, the current automotive HUD systems could be further improved in terms of the system functions and the interface/interaction design so as to offer better utility and usability.

For any existing human-machine system, examining the current use practices and the problems and issues perceived by the users is an essential step towards design improvement and innovation; its importance has been repeatedly emphasized in the product design and user experience literature (ISO 9241-210:2010; Hartson and Pyla 2012; Yayici 2014). The design of automotive displays, including HUD, would be no exception to this. According to Bhise (2011), studying the actual usage conditions and driving situations when automotive displays are used can provide insights into the driver's tasks, informational needs, time constraints, and environmental conditions.

Despite the importance, however, little knowledge seems currently available concerning the contexts of system use and user-perceived problems/challenges for the existing automotive HUD systems. Numerous human factors (HF) and HCI studies have been conducted on automotive HUD systems - the existing HF/HCI studies on automotive HUD may be classified largely into four groups in terms of their purposes: 1) demonstrating the advantages of HUD over conventional HDD (Rutley 1975; Sojourner and Antin 1990; Srinivasan and Jovanis 1997; Liu 2003; Liu and Wen 2004); 2) developing novel automotive HUD functions/applications (Doshi, Cheng and Trivedi 2009; Charissis and Papanastasiou 2010; Fujimura et al. 2013; Kim et al. 2013; Park et al. 2013; Tran, Bark and Ng-Thow-Hing 2013; Bark et al. 2014; Yoon et al. 2014; Haeuslschmid et al. 2015); 3) comparing HUD interface design alternatives (Watanabe et al. 1999; Plavšic et al. 2009; Huang et al. 2013; Guo et al. 2014; Pfannmüller et al. 2015; Gregoriades and Sutcliffe 2018) and 4) determining the relative importance of different HUD information items (Moon and Park 1998; Bergman 2011; Park, Kim and Chong 2012; Huang et al. 2013; Guo et al. 2014). However, the existing studies rarely dealt with the system use practices and the problems/issues perceived by the users.

2.1.3 Research Objectives for HUD Information Items

Addressing these key knowledge gaps regarding the two research questions for HUD information items would contribute to the future ergonomics design of automotive HUD systems, which could adequately present only the necessary and important information according to the driving situation at hand. Therefore, the current study conducted a user survey with experienced automotive HUD users, to 1) determine the perceived importance of various HUD information items displayed by the existing commercial automotive HUD systems, and to 2) examine the contexts of use and the user-perceived design improvement points for high-priority HUD information items. User surveys have been used to understand product use practices and user wants and needs in a variety of product design contexts (Rubin and Chisnell 2008; Goodman, Kuniavsky and Moed 2012).

2.2 CMS Display Layouts

2.2.1 Literature Review on Research Question 3 (What are the design characteristics of CMS display layouts that can facilitate driver information processing?)

Recently, a few ergonomics studies investigated the benefits of CMS and the impacts of different spatial arrangements of CMS displays. Mohamed Ali and Fatin Bazilah (2014) conducted an on-road driving study to observe the behaviors of drivers while they were driving a mirrorless vehicle with CMS. The mirrorless vehicle had a CMS consisting of cameras and three LCD screens on the dashboard: the left and right side-view displays were placed on the left and right side of the dashboard, respectively, and the rear-view display, at the location of speedometer of a conventional car. The study reported that: compared with the conventional mirror system, the CMS improved the driver's attention to the road outside and reduced repetitive head movements for obtaining side- and rear-view information. However, it was also found that the study participants frequently looked down to see the rear-view display; the study stated that this dangerous behavior should be rectified by changing the position of the rear-view display.

Large et al. (2016) conducted a driving simulator study to evaluate five different layouts of three in-vehicle displays (one rear- and two side-view displays) against the traditional mirror system. The study participants conducted prescribed overtaking maneuvers using each of the six arrangements of displays, and, their visual behavior, driving performance and opinions were examined. The overtaking task trials neither demanded rapid decision-making nor involved particularly dangerous events – while driving in a generic motorway scenario, the participants were given the instructions such as 'move into the middle lane when it is safe to do so'. The results showed reductions in decision time for lane changes and eyes-off-the-road time while using the in-vehicle electronic displays. Subjectively, drivers preferred layouts that most closely matched existing mirror locations, where aspects of real-world mapping were largely preserved. Also, it was found that locating the rear-view display at a lower position in the dashboard area resulted in undesirable visual behaviors and poor subjective responses of participants.

Schmidt et al. (2016) comparatively evaluated the conventional side-view mirror system and three layouts of two electronic side-view displays. The three display layouts placed side-view displays at following locations: (1) at the driver and passenger door panels, (2) close to the steering wheel on the air vent grids and (3) next to the A-pillars of the vehicle. The study participants drove on a real motorway of 14.7 km in length using each of the four systems and their glance behavior and preference ratings were recorded. The four monitor/mirror systems did not reveal any statistically significant differences in the mean glance frequency or duration. The most preferred one was the 'next to the A-pillars' layout.

Despite the past studies, however, overall, the current body of knowledge regarding the ergonomics design of CMS seems scant. One knowledge gap pertains to the evaluation of different CMS display layouts in dangerous, time- and safety-critical driving situations, which involve events, such as sudden stop of a vehicle ahead, cut-in of a vehicle from an adjacent lane, appearance of obstacle, high-speed lane change, etc. – the previous studies considered mostly normal driving situations that did not involve these events. Evaluating different CMS display layouts in dangerous situations is important as these situations are where the use of the mirrors/displays becomes most critical and the design decisions can make a life or death difference. The importance of utilizing dangerous situations is highlighted in some previous studies. According to Gish and Staplin (1995), reliable assessment of HUD efficacy requires a test methodology that utilizes worst-case conditions such as exposure to unexpected events requiring a time-critical response. Another study by Wickens (2001) stated that examination of new technology requires investigators to identify the nature of the operator response in the worst-case scenario.

2.2.2 Literature Review on Research Question 4 (What are the design characteristics of CMS display layouts that can reduce physical demands of driving?)

Previous literature points to the possible impacts of CMS display layout design on the upper body movements. Mohamed Ali and Fatin Bazilah (2014), on the basis of their observation, suggested that a CMS with displays located in the dashboard area might reduce drivers' repetitive head movements. In a study by Large et al. (2016), the participants commented that when using some CMSs, they did not need to move their head as much as they would have with the traditional mirrors. The participants' comments included: 'less effort to rotate my head,' 'required less movement and felt comfortable,' and 'loved this one...very easy to glance and check.' In a study by Schmidt et al. (2016), some participants proposed positioning CMS electronic displays closer to the steering wheel so as to reduce the number of head movements. Furthermore, Alliance of Automobile Manufacturers and Tesla Motors, Inc. (2014) and Terzis (2016) suggested that a CMS display layout could be designed to assist drivers with reduced mobility, including older drivers, with maintaining peripheral vision of critical areas.

Despite the possibility of reducing physical demands of driving through CMS display layout design, however, very few studies seem to have empirically investigated the effects of CMS display layout design on measures of physical demands of driving. Especially, the authors are not aware of any research study that quantitatively examined driver's eye and head movements required to check CMS displays, both of which represent important elements of the physical demands of driving. Consequently, little design information is currently available, and this knowledge gap hampers creating usable CMSs.

2.2.3 Research Objectives for CMS Display Layouts

Addressing these key knowledge gaps regarding the two research questions for CMS display layouts would enhance the ergonomics design of CMS, which could improve driving performance, safety, and comfort compared to the traditional mirror system. Therefore, the current study conducted a driving simulator experiment to comparatively evaluate three different CMS side-view display layouts along with the traditional side-view mirror arrangement in a dangerous driving scenario, in terms of 1) driver information processing (driving performance and safety) and 2) physical demands of driving. The experiment task was making a safety-critical lane change in the presence of an obstacle and other vehicles, imposing non-trivial physical demands on the driver's eye and head musculature in addition to cognitive demands.

Chapter 3

A Survey Study on Head-Up Display (HUD) Information Items

3.1 Research Methods

3.1.1 Survey Participants

A total of fifty-one drivers participated in this survey study. The participants' mean age and mean driving experience were 36.0 years (SD=6.82, Range: 23-50) and 13.7 years (SD=6.25, Range: 3.5-25), respectively. All of the participants had sufficient prior experience of using existing commercial automotive HUD systems – their mean HUD experience was 2.59 years (SD=2.00, Range: 1-10). On average, the participants drove 1.97 hours per day (SD=0.98, Range: 0.5-5). The driving contexts varied, including commute, school run, shopping, and business and pleasure trips. The participants owned a total of fifty-three vehicles (one participant owned three vehicles). According to the car classification system of the European Commission

(1999), among the fifty-three vehicles were seventeen D-segment large cars, nineteen E-segment executive cars, three F-segment luxury cars, thirteen J-segment sport utility cars, and one S-segment sport car.

3.1.2 Data Collection and Analyses

This study considered information items displayed by existing commercial automotive HUD systems. A total of twenty-two information items (Table 3.1) were identified by examining Original Equipment Manufacturer (OEM) HUD systems available as built-in options from the seventeen major automakers (Audi, BMW, Buick, Cadillac, Chevrolet, Citroën, Honda, Hyundai, Kia, Land Rover, Lexus, Mazda, Mercedes-Benz, MINI, Peugeot, Toyota, and Volvo) and various aftermarket HUD systems mostly integrating with smartphone applications (e.g., Carloudy, Exploride, Garmin HUD, HUDWAY, Navdy, and SenseHUD).

Table 3.1: Twenty-two information items displayed by existing commercial HUD systems

Current speed	Turn signal indicators
Speed limit	Forward collision warning
Turn-by-turn navigation instructions	Battery voltage
Maintenance warning	Lane departure warning
Cruise control status	Current time
Audio player status	Eco status (Instantaneous/average fuel consumption or ECO indicator)
Traffic sign	Engine operating status (Engine temperature or oil pressure)
Distance to destination	Daily information (Date, weather)
Gear position	Call information (Incoming call, caller's ID, call history, or phone book entries)
RPM	HVAC status (Heating, ventilating, and air conditioning status)
Low fuel warning	Driving distance

For each information item in Table 3.1, each study participant was instructed to subjectively rate the level of importance of the information item using a five-point semantic differential scale (1-'Absolutely unimportant', 2-'Unimportant', 3-'Neutral', 4-'Important', 5-'Absolutely important'). This response format was employed based on the research finding of Friborg, Martinussen and Rosenvinge (2006) that in measuring positive psychological constructs (such as 'importance' investigated in the current study), the semantic differential scale format produced less acquiescence bias than the Likert scale without lowering psychometric quality. Also, the participants were asked to indicate if they had used any HUD systems displaying the information, that is, if they had prior 'information item experience' – note that while everyone of the fifty-one participants had at least one year of experience in using HUD system(s) (prior 'HUD experience'), not every participant had experienced all the twenty-two HUD information items, because the existing HUD systems display different subsets of the twenty-two information items. If the participants had prior experiences of using HUD systems displaying the information item, they were instructed to respond to two survey items, which were: (1) Describe the context of information use, and (2) Describe possible design improvement points (of the HUD system[s] that you have used). The data collection protocol had been approved by the Institutional Review Board of Seoul National University.

The related survey items are shown in Figure 3.1.

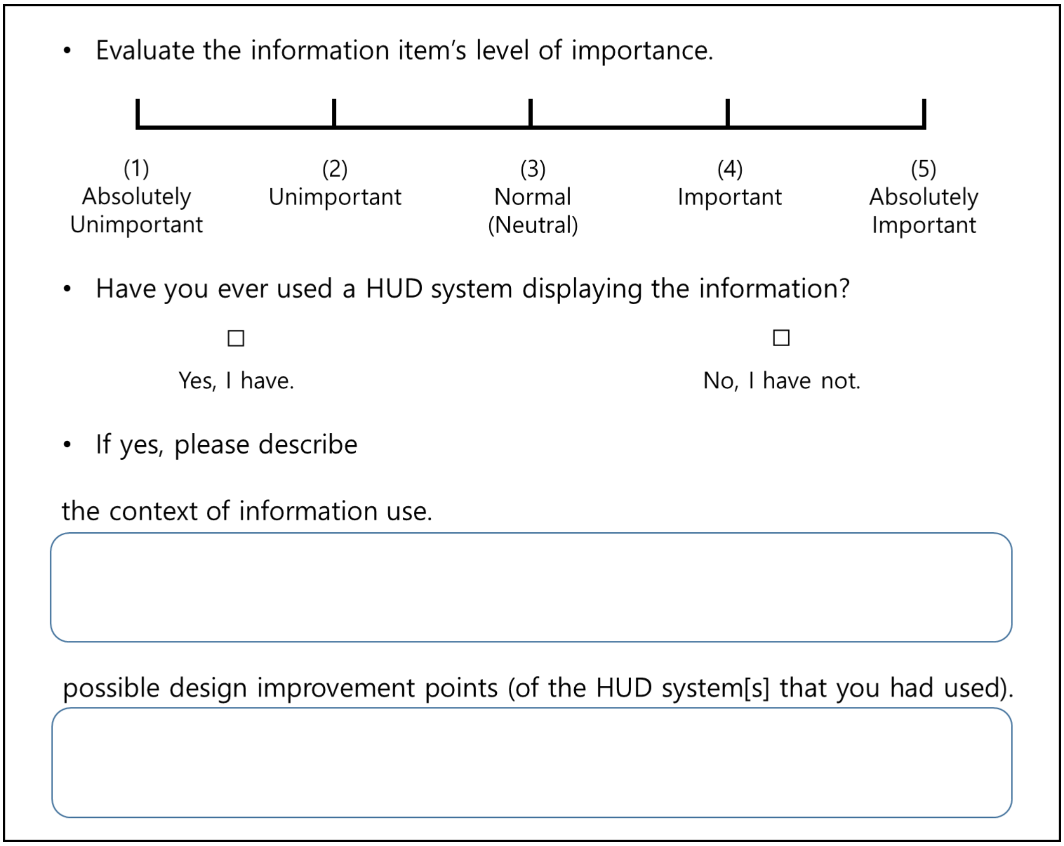

Figure 3.1: The survey questions

For each information item, the number of participants with prior information item experience and that of the participants without such experience were determined. Also, for each information item, the averages of the importance rating scores were computed for three different groups of participants – 1) all participants, 2) the participants with prior information item experience and 3) the participants without prior information item experience, respectively. This was to characterize the information item's perceived importance level.

The semantic differential scale in Figure 1 is an ordinal scale. From a strictly theoretical point of view, means, standard deviations and other statistics involving them should not be used with ordinal data (Stevens 1946; Jamieson 2004). However, it is commonly accepted that parametric statistics are robust enough to be applied to ordinal data without concerns for getting the wrong results (Pell 2005; Carifio and Perla 2008; De Winter and Dodou 2010; Norman 2010; Lovelace and Brickman 2013). Such parametric analyses with ordinal data have been widespread in the human factors and psychology literature for decades with fruitful results (Bradley and Lang 1994; Hsu, Chuang and Chang 2000; Friborg, Martinussen and Rosenvinge 2006; Parolini, Patterson and Winston 2009).

Based on the perceived importance and number of participants with prior information item experience, some high-priority HUD information items were identified, which were considered in the current study for examining the contexts of use and design improvement points. For each of the high-priority HUD information items, the survey responses (comments) of the participants were examined and refined into simple statements, each of which contained one simple concept, idea or fact. For each statement, the associated frequency (the number of participants who made the statement) was recorded. An affinity diagram analysis was conducted on the simple statements dataset to identify themes or topics. A total of three graduate students with several years of research experience in vehicle ergonomics participated in the affinity diagram analysis in the following process:

1) Examining each statement, characterizing it and discussing its meaning.
2) Exploring for the common characteristics/similarities across the statements.
3) Grouping the statements that have an affinity/topical similarity into a cluster.
4) Making a label for each cluster to help assign new statements appropriately.
5) Modifying (creating/growing/merging/splitting) the clusters and thereby the labels until all of the statements are assigned to proper clusters.

For each theme/topic (cluster), design implications were derived from the corresponding simple statements through deductive inferences. The analyses of the survey response data were based on the contextual analysis methods described in Hartson and Pyla (2012).

3.2 Perceived Importance of Various HUD Information Items Displayed by the Existing HUD Systems

3.2.1 Results

Table 3.2 provides a summary of the survey results. For each of the twenty-two information items considered, it presents the average importance rating scores computed for 1) all participants, 2) the participants with prior information item experience and 3) the participants without prior information item experience, respectively (hereafter, simply R_all, R_exp, and R_inexp, respectively). It also provides the number of participants with prior information item experience and that of the participants without such experience (hereafter, simply N_exp and N_inexp, respectively) for each information item.

Table 3.2: Tabular summary of survey results

Information	R_all (N)	R_exp (N_exp)	R_inexp (N_inexp)
Current speed	4.73 (51)	4.73 (51)	N/A (0)
Speed limit	4.59 (51)	4.64 (36)	4.47 (15)
Turn-by-turn navigation instructions	4.37 (51)	4.48 (48)	2.67 (3)
Maintenance warning	3.98 (51)	4.69 (26)	3.24 (25)
Cruise control status	3.80 (51)	4.38 (32)	2.84 (19)
Audio player status	3.45 (51)	3.90 (29)	2.86 (22)
Traffic sign	3.35 (51)	3.65 (17)	3.21 (34)
Distance to destination	3.25 (51)	3.47 (17)	3.15 (34)
Gear position	3.24 (51)	3.5 (18)	3.09 (33)
RPM	3.24 (51)	3.83 (12)	3.05 (39)
Low fuel warning	3.02 (51)	4.12 (26)	1.88 (25)
Turn signal indicators	2.96 (51)	3.42 (12)	2.82 (39)
Forward collision warning	2.94 (51)	3.17 (6)	2.91 (45)
Battery voltage	2.67 (51)	3.17 (6)	2.6 (45)
Lane departure warning	2.55 (51)	2.75 (4)	2.53 (47)
Engine operating status	2.45 (51)	4.5 (2)	2.37 (49)
Current time	2.43 (51)	3.29 (7)	2.30 (44)
Eco status	2.43 (51)	2.67 (3)	2.42 (48)
Daily information	2.08 (51)	2.33 (3)	2.06 (48)
Call information	1.94 (51)	3 (11)	1.65 (40)
HVAC status	1.82 (51)	2.5 (4)	1.77 (47)
Driving distance	1.78 (51)	2.56 (9)	1.62 (42)
Grand Mean	3.05 (1122)	4.06 (379)	2.53 (743)
Grand SD	1.42 (1122)	1.06 (379)	1.30 (743)

Figure 3.2 graphically illustrates the variation in N_exp across the twenty-two information items.

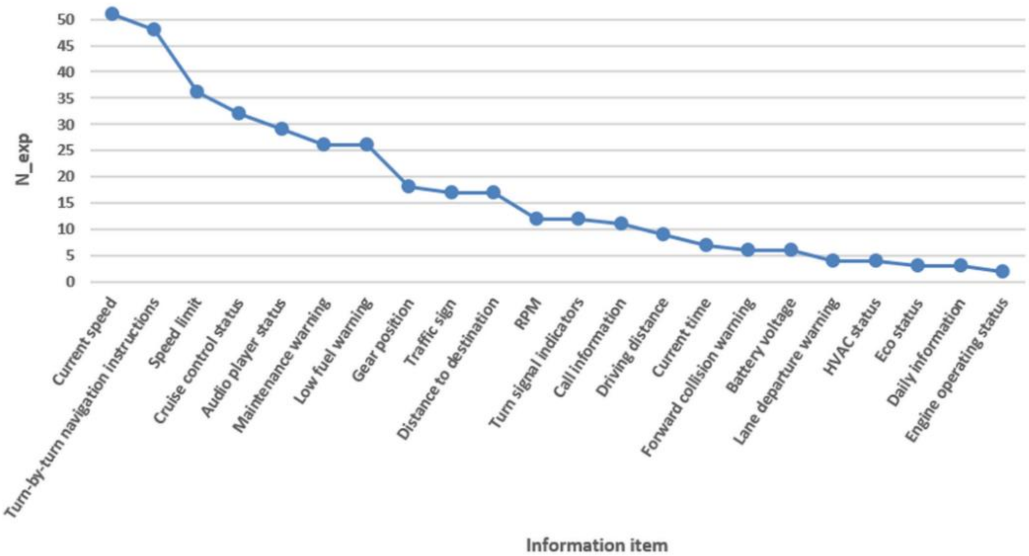

Figure 3.2: The number of participants with prior 'information item' experience (N_exp) for each information item

Figure 3.3 visually depicts the variation in each of the three average importance rating scores (R_all, R_exp, and R_inexp) across the information items.

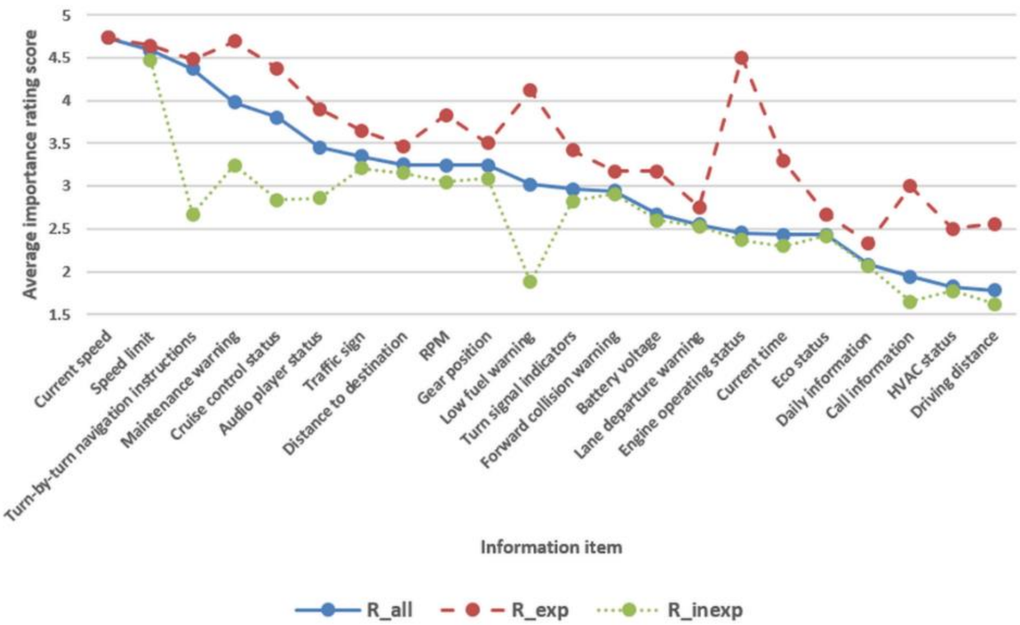

Figure 3.3: The three average importance rating scores for each information item: the averages for 1) all participants (R_all), 2) the participants with prior 'information item' experience (R_exp) and 3) the participants without prior 'information item' experience (R_inexp)

3.2.2 Discussion

This study investigated the perceived importance of various automotive HUD information items by surveying drivers with significant prior experience of using automotive HUD systems. Fifty-one drivers (average years of HUD experience: 2.59 years) participated and subjectively evaluated a total of twenty-two information items in perceived importance. The information items were those displayed by existing commercial automotive HUD systems.

N_exp was found to vary greatly across the twenty-two information items (Figure 3.2). All of the fifty-one participants had prior experience of using current speed; and, forty-eight had experience with turn-by-turn navigation instructions. Most of the existing commercial HUD systems support these two information items (Huang et al. 2013). On the other hand, for fifteen out of the twenty-two information items, N_exp was less than half of the total number of the participants. Also, five information items, that is, lane departure warning, HVAC status, eco status, daily information and engine operating status, had N_exp less than five. The large variability in N_exp seems to reflect the fact that commercial automotive HUD systems display different sets of information items, which have a small number of common elements (Bergman 2011; Park, Kim and Chong 2012; Kim and Pan 2015).

It appears that no consensus currently exists as to the choice of information items for automotive HUDs among the manufacturers of automotive HUD systems, except for a few information items such as current speed and turn-by-turn navigation instructions.

The twenty-two information items varied greatly in the three average perceived importance ratings, that is, R_all, R_exp and R_inexp (Figure 3.3, Table 3.2). R_all ranged from 1.78 to 4.73 on the five-point scale shown in Figure 3.1. Only three information items had R_all greater than four ('important'). They were: current speed, speed limit and turn-by-turn navigation instructions. R_exp ranged from 2.33 to 4.73. Seven information items had R_exp greater than four. They were: current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status, low fuel warning and engine operating status. R_inexp ranged from 1.62 to 4.47. Only speed limit had R_inexp greater than four - note that R_inexp was not computed for current speed as all fifty-one participants had prior information item experience for it.

A notable observation from Figure 3.3 was that R_exp was larger than R_inexp, consistently across the information items. The differences between R_exp and R_inexp (R_exp - R_inexp) ranged from 0.17 to 2.24 points with an average difference of 0.88 points. In order to examine the impacts of survey participants' prior experience of using a HUD information item on its perceived importance rating, post-hoc statistical comparisons of R_exp and R_inexp were conducted as follows:

For eight out of the twenty-two information items, N_exp and N_inexp were both large enough to allow statistical testing of the mean difference without concerns about low statistical power – they were speed limit, maintenance warning, cruise control status, audio player status, traffic sign, distance to destination, gear position, and low fuel warning. For these information items, t-tests were conducted to understand the impact of user's prior information item experience on the evaluation of the item's importance. The statistical tests were conducted at an alpha level of 0.05 using SPSS 21.0 (SPSS Inc., Chicago, USA).

Four information items showed statistically significant difference between R_exp and R_inexp – they were maintenance warning, cruise control status, audio player status, and low fuel warning. In other words, prior information item experience was associated with a statistically and practically larger mean importance rating for half of the eight information items considered. Figure 3.4 presents the group means (R_exp and R_inexp) and the t-test result for each of the four information items.

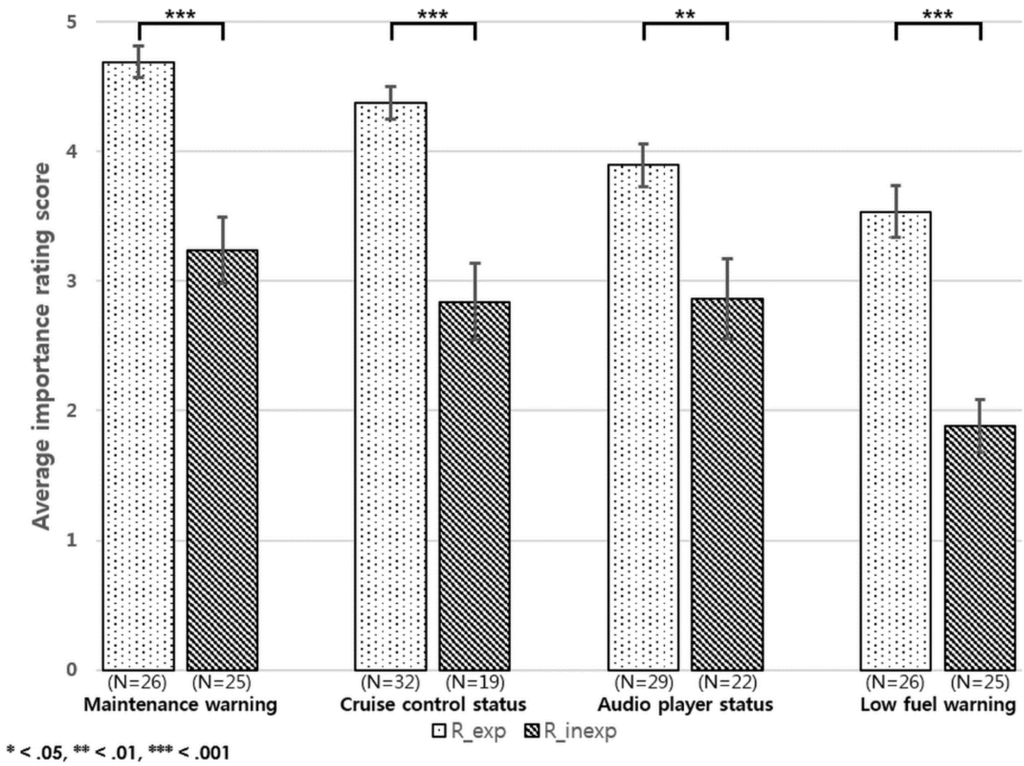

Figure 3.4: The statistically significant differences between the average importance rating scores for the participants with prior 'information item' experience (R_exp) and the participants without the 'information item' experience (R_inexp)

The above results are thought to indicate that: even among the drivers with significant prior HUD experience, those who have experienced using a particular HUD information item tend to better recognize and appreciate its importance than those without such information item experience. It would be reasonable to regard the collective judgment of those with prior information item experience as more accurate than that of those without such experience.

While it is not entirely clear what gave rise to the above tendency associated with information item experience in the subjective importance rating, it is thought that assessing the importance of an information item without real use experience and therefore solely based on mental simulation may be cognitively difficult for most drivers. Actual information item experience in the real or realistic HUD use contexts may be essential for properly evaluating information items' importance. Relatedly, Bergman (2011) reported a finding that lends support to the importance of actual use experience in the evaluation of automotive HUD systems - in this study, the participants filled out a questionnaire measuring the attitudes and perceptions towards the use of HUD such as willingness to use before and after using a prototype HUD system in real traffic for four days. The study found that the participants' responses became more positive after experiencing the prototype HUD system. It further suggested that user studies on automotive HUDs should recruit subjects with extensive HUD experiences who feel HUD use as a natural part of their driving experience.

In light of the impacts of prior information item experience described above, the results shown in Figure 3.3 must be interpreted with caution. As for the information items for which N_exp was large, R_exp can be considered good estimates of their true importance. However, for the information items for which

N_exp was small, R_exp cannot be regarded as reliable estimates due to the small sample size; and, R_all may underestimate their true importance. For these information items, further studies with more participants with prior information item experience are needed.

As mentioned earlier, current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status, low fuel warning and engine operating status had R_exp greater than four ('important'). For engine operating status, N_exp was only two; thus, its R_exp could not be considered a reliable estimate of information item importance. For the other six information items, R_exp were computed based on a large number of data points (N_exp ranged from 26 to 51). Hence, these six information items were considered the high-importance items.

Among the six high-importance items, only the current speed and speed limit were identified as important by the majority of the previous studies that examined drivers without prior HUD experience (Bergman 2011; Park, Kim and Chong 2012; Huang et al. 2013; Guo et al. 2014). The other items (turn-by-turn navigation instructions, maintenance warning, cruise control status, and low fuel warning) were not among the high-importance items. These differences in the results are thought to indicate the significance of actual HUD experience in subjectively evaluating the importance of information items - again, recruiting experienced HUD users is deemed essential for user studies on automotive HUDs (Bergman 2011).

The high-importance items (current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status, low fuel warning) seem to have some distinct characteristics when compared with the rest. They are as follows:

- They are directly related to vehicle longitudinal or lateral control, and, therefore, demand frequent or continuous attention from the driver,
- They demand fast perception and reaction from the driver,
- They are critical for driving performance and safety, and, therefore, demand correct information processing, and/or
- They cannot be obtained from the outside road view.

It is worth noting that the six high-importance information items correspond to the primary tasks of the driving task classification scheme described by Bubb (2011) while the rest of the items correspond to secondary and tertiary tasks. The primary tasks are the ones necessary for the driver to keep the vehicle on the road and to proceed according to the planned route. The secondary tasks are not essential for keeping the vehicle on the road but need to be performed to support the primary driving tasks. The tertiary tasks do not directly contribute to the driving itself but enhance the driver's convenience.

The current result that the high-importance items for automotive HUD systems pertain to the primary driving tasks is consistent with the design recommendation by Tonnis, Broy and Klinker (2006). The study attempted to determine the optimal allocation of information items to different in-vehicle displays. It recommended that the information items related to the primary tasks be best shown in the windshield area through HUD. The current result is also congruent with the recommendation from SAE J2831 (2012) that visual messages related to driving control activities be presented near the driver's center of attention so as to minimize looking away from the road way.

Interestingly, audio player status was perceived as a relatively important information item even though pertaining to a tertiary driving task – its R_exp was 3.90 ($N\_exp = 29$) (Figure 3.3, Table 3.2). This finding seems to reflect the fact that listening to the radio or music while driving is common among drivers and it is an important part of the overall driving experience (Knobloch and Zillmann 2002).

It may be worth pointing out that forward collision warning and lane departure warning were not identified as high-importance information items despite their relevance to driving safety - their R_exp were 3.17 and 2.75, respectively. Again, their true importance levels cannot be accurately estimated on the basis of the current study results as the sample sizes for them (N_exp) were too small (six for forward collision warning and four for lane departure warning). Nonetheless, the authors speculate that their importance levels are not high, on the basis of the following. 1) The information necessary for avoiding forward collision or lane departure can be directly obtained from the outside road view. The visual warnings would be useful only when the driver is inattentive to the outside road view. 2) Images displayed through HUDs could mask the critical visual information in the real world and actually hinder its effective processing, especially if they are not designed well. 3) Visualization through HUD alone may not be effective in delivering the warnings to the driver. Existing human factors guidelines, for example, those in Green et al. (1994), generally recommend that warnings needing immediate attention should be provided through an auditory channel.

Perhaps, an effective solution might be to display the two information items via multiple channels simultaneously (e.g., visually through a HUD and also in an auditory channel) and only when needed. The multimodal HUD (Stevens et al. 2002;

ISO/TR 16352:2005; Oh, Ko and Ji 2016) and driver state monitoring technologies (Ji, Zhu and Lan 2004) could be utilized in combination to create such 'active HUD' systems (Doshi, Cheng and Trivedi 2009; Dijksterhuis et al. 2012; Langner et al. 2016). Further studies are needed to explore and evaluate different design alternatives for delivering the two information items.

3.3 Contexts of Use and User-Perceived Design Improvement Points for High-Priority HUD Information Items

3.3.1 Results

Among the twenty-two HUD information items, some high-priority information items, including the above six high-importance information items (current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status, low fuel warning), were identified, on the basis of the following:

As shown in Table 3.2 above, eleven information items had the average importance ratings for all participants (R_all) greater than three ('Neutral'). They were: current speed, speed limit, turn-by-turn navigation, maintenance warning, cruise control status, audio player status, traffic sign, distance to destination, gear position, RPM and low fuel warning. The eleven information items also corresponded to the top half of the twenty-two items in terms of the number of participants with prior information item experience (N_exp) – it ranged from 12 to 51, with an average of 28.4 for the top eleven information items, and from 2 to 12, with an average of 6.10 for the others. Participant's prior information item experience was crucial in light of the research objective (examining actual usage contexts and design improvement points for HUD information items). The eleven high-priority HUD information items in terms of the perceived importance and number of participants with prior information item experience were considered in the current study for examining the contexts of use and design improvement points.

Tables 3.3~3.13 summarize the participants' responses to the survey regarding the context of use and design improvement points for each of the eleven information items. Each table provides simple statements obtained by refining the participants' original comments and their associated frequencies.

Table 3.3: Summary of participants' survey responses: current speed (total 51 participants)

	Statements	Frequencies
Context of use	"I use it all the time while driving."	24
	"It helps me comply with the speed limits in the enforcement sections."	23
	"It is useful on the highway."	5
	"It helps me control the driving speed and prevent speeding."	4
Design improvement points	"When speeding, I want it to be displayed with visually conspicuous effects such as red color or blinking."	5
	"I want its font size to be increased for good visibility."	4
	"I want it to be displayed in various colors for good visibility."	3
	"It slightly lags behind the actual value."	3
	"I want it to be displayed on or near the driver's normal line-of-sight or I want to be able to adjust its location."	2
	"If displayed with speed limit, it would enhance driving safety."	1
	"I want it to be displayed with RPM and gear position."	1

Table 3.4: Summary of participants' survey responses: speed limit (total 36 participants)

	Statements	Frequencies
Context of use	"It helps me comply with the speed limits in the enforcement sections."	16
	"It is useful on the highway."	4
	"It is useful when I overlook or have difficulty detecting the road sign due to the unfamiliarity with the driving route."	2
Design improvement points	"When speeding, I want it to be displayed with visually conspicuous effects such as red color or blinking."	7
	"I want the HUD system to provide accurate speed limit information through fast and automatic updates of the on-board navigation system."	6
	"I want it to be displayed all the time, regardless of whether the navigation system is activated or not."	4
	"I want it to be displayed only in the actual enforcement sections."	3
	"I want to be able to choose whether or not to display it."	2

Table 3.5: Summary of participants' survey responses: turn-by-turn navigation (total 48 participants)

	Statements	Frequencies
Context of use	"It supports wayfinding especially at intricate areas or in unfamiliar environments."	22
	"It keeps me informed of the route even when the center console display is occupied by information items other than navigation (e.g., audio player, digital multimedia broadcasting)."	1
Design improvement points	"I want it to provide a wider variety of information in greater detail, especially for complex routes (e.g., intersections, interchanges)."	13
	"I rarely use HUD navigation, since the provided information is inaccurate one transferred from the on-board navigation system of poor/unreliable wayfinding performance. Instead, I mostly use non-HUD navigation systems such as smartphone applications and aftermarket devices."	8
	"On-board navigation systems of foreign cars should be improved to provide accurate and efficient route guidance in the domestic road/traffic conditions."	6
	"I want it to be displayed in various colors for good visibility."	3
	"I want the visualization of information (e.g., directions and maps) to be more realistic and understandable."	3
	"I want the HUD system to provide accurate information reflecting frequently changing road traffic conditions through fast and automatic updates of the on-board navigation system."	2
	"I want it to show a brief mark of the current location."	2
	"Adding the cardinal points would be useful for grasping the driving direction."	1
	"It would be of great help to provide a lane change instruction as well."	1

Table 3.6: Summary of participants' survey responses: maintenance warning (total 26 participants)

	Statements	Frequencies
Context of use	"It allows immediate detection of the vehicle's problems and timely measures against them, which might have been overlooked otherwise."	5
Design improvement points	"I not only want a warning sign but also a detailed explanation for the problem and its solution."	6
	"I want its size to be larger."	1

*Note: Maintenance warning refers to the warning sign presented when maintenance is required (for tire pressure, engine oil, brake system, coolant, and so on).

Table 3.7: Summary of participants' survey responses: cruise control status (total 32 participants)

	Statements	Frequencies
Context of use	"It is useful on the highway."	16
	"It helps me comply with the speed limits in the enforcement sections."	3
Design improvement points	"It does not have to be displayed on the HUD, because it just clutters the limited space of the HUD screen."	3
	"When I adjust the cruise control settings, I want it to be immediately displayed without lags."	2
	"I want it to be displayed along with speed limit."	2

Table 3.8: Summary of participants' survey responses: audio player status (total 29 participants)

	Statements	Frequencies
Context of use	"It helps me check and manipulate (e.g., search, select, change) currently playing audio tracks or radio stations."	20
	"I frequently use it, as I always listen to music while driving."	7
Design improvement points	"It does not have to be presented on the HUD because it just obstructs my field of view."	1
	"I want the volume level to be displayed as well."	1
	"I want its font size to be increased for good visibility."	1

*Note: Audio player status refers to information about currently playing audio tracks or radio stations (e.g., title of a song, radio frequency).

Table 3.9: Summary of participants' survey responses: traffic sign (total 17 participants)

	Statements	Frequencies
Context of use	"It supports wayfinding at intricate areas or in unfamiliar environments."	5
	"It is useful on the highway."	4
	"It is useful when I overlook or have difficulty detecting the road sign due to the poor visibility of the road ahead."	2
Design improvement points	"I want the HUD system to provide accurate information reflecting frequently changing road traffic conditions through fast and automatic updates of the on-board navigation system."	3
	"I want to be able to turn it on or off regardless of whether the on-board navigation system is operating or not."	1
	"It should be designed to match up with the actual roadway signs."	1

*Note: Traffic signs include regulatory signs (e.g., no entry signs, no parking signs), warning signs (e.g., sharp curve, falling rocks, slippery road, bumpy road, fog area), and guide signs (e.g., street names, expressway signs).

Table 3.10: Summary of participants' survey responses: distance to destination (total 17 participants)

	Statements	Frequencies
Context of use	"It is useful when traveling to an unfamiliar destination."	5
	"It helps me estimate arrival times and schedule trips."	3
Design improvement points	"It does not have to be displayed on the HUD because I can easily get it from the on-board navigation or sometimes from the road signs."	3
	"I want the HUD system to provide accurate information reflecting frequently changing road traffic conditions through fast and automatic updates of the on-board navigation system."	2

Table 3.11: Summary of participants' survey responses: gear position (total 18 participants)

	Statements	Frequencies
Context of use	"It is useful for checking and shifting gears in manual shift mode."	7
	"It is useful for sporty driving."	5
	"It is useful for economical driving."	3
Design improvement points	"Since I usually drive in automatic mode, it is not that necessary."	5
	"I want it to be displayed with engine RPM."	3
	"I do not use it often."	2
	"I want to be able to choose whether or not to display it."	2
	"I want it to be displayed even when I drive in automatic mode (e.g., D1~D7)."	2
	"I want its visual design to be aesthetically more appealing."	2

Table 3.12: Summary of participants' survey responses: RPM (total 12 participants)

	Statements	Frequencies
Context of use	"It is useful for sporty driving."	5
	"It is useful for checking and shifting gears in manual shift mode."	4
	"It is useful for economical driving."	1
Design improvement points	"I want it to be displayed only in sport mode, not in usual automatic mode."	2
	"It does not have to be displayed on the HUD because I can estimate the RPM by hearing the engine sound."	1
	"It slightly lags behind the actual value."	1
	"I want its design to be visually more outstanding for driving pleasure."	1
	"I want it to be displayed with gear position."	1

Table 3.13: Summary of participants' survey responses: low fuel warning (total 26 participants)

	Statements	Frequencies
Context of use	"It allows immediate identification of the low fuel level."	2
Design improvement points	"It does not have to be displayed on the HUD, because checking the instrument panel or hearing auditory warning is enough."	5
	"I want it to display the distance to empty all the time regardless of the fuel level."	1
	"I want it to display the instantaneous fuel consumption rate as well, which would be useful for economical driving."	1
	"It is currently displayed where the turn-by-turn navigation is being presented, so drivers may become distracted or confused by the warning, and may miss the navigation instructions."	1

3.3.2 Discussion

The current study conducted a user survey on the contexts of system use and user-perceived design improvement points for the existing commercial automotive HUD systems focusing on eleven high-priority HUD information items. The survey participants were experienced automotive HUD users. Some major observations from the survey results (Tables 3.3~3.13) are discussed in what follows.

Speed control

Many survey participants responded that checking current speed, speed limit and/or cruise control status through HUD helped control the vehicle speed, and, especially, comply with the speed limits (Tables 3.3, 3.4 and 3.7). Since speed control is a fundamental element of driving, which continuously requires the driver's attention, providing relevant information at an easily accessible location using HUD would be beneficial. Multiple previous studies (Rutley 1975; Sojourner and Antin 1990; Liu and Wen 2004; Doshi, Cheng and Trivedi 2009) showed that drivers were better at controlling the vehicle speed and adhering to the speed limit when using HUD than HDD. Rutley (1975) stated that drivers' enhanced awareness of the speed-related information through HUD could be particularly useful considering the drivers' frequent misjudgment of the vehicle speed.

Some participants wanted current speed and speed limit to be displayed with conspicuous effects such as red color or blinking in case of speeding (Tables 3.3 and 3.4). Color- or blink-coding seems to be a good design strategy in that they are well suited for vehicle warnings requiring immediate attention (Green et al. 1994; Stevens et al. 2002; ISO/TR 16352:2005; SAE J2831 2012), and, they can provide additional information without visual clutter. However, such visual effects in HUD should be carefully applied not to compel too much attention or annoy the drivers (Ward and Parkes 1994; Tufano 1997). One possible design solution may be to change the visual conspicuity (e.g., changing colors or blinking frequencies), depending on the vehicle speeds. Besides the user demands, given the importance of speed control in driving, further efforts may be warranted to develop new HUD concepts for supporting it. Indeed, some prototype HUD systems have been proposed so as to support longitudinal speed control. Examples include a HUD for presenting oncoming traffic volume (Charissis and Papanastasiou 2010) and that for visualizing the vehicle braking distance (Plavšic et al. 2009).

Highway driving

Some participants commented that accessing current speed, speed limit, cruise control status and traffic sign through HUD was particularly useful on the highway (Tables 3.3, 3.4, 3.7 and 3.9). These results seem to reflect that 1) reducing information access costs for speed control-related information is important on the highways where speeding occurs frequently and speed cameras are mainly installed, and 2) rapidly detecting traffic signs is essential for correct and safe vehicle maneuvers at interchanges and ramps and in the areas with potential hazards. Also, since the driver's visual scanning area becomes narrower and viewing distance becomes farther at higher speeds (Sanders and McCormick 1993; Park et al. 2016), HUD would be particularly beneficial for highway driving.

Future study might explore new HUD functions and interface designs for highway driving. Especially, observational studies of drivers on highways would be useful for identifying drivers' information needs in that particular driving environment. Also, adaptively controlling the HUD focal distance and HUD image location according to the driving environment may improve the usefulness of automotive HUD. Relatedly, Park et al. (2016) have suggested that HUD images be focused at a farther distance and located closer to the center of line-of-sight at higher speeds to minimize eye transition/accommodation.

Engine/transmission control

Some study participants responded that checking gear position and RPM through HUD was useful for gear shifting in manual shift mode, and for sporty or economical driving (Tables 3.11 and 3.12). These responses are understandable as the driver needs to check gear position and RPM frequently in such driving contexts.

One possible design idea for automotive HUD is to change the HUD interface adaptively, according to the driving mode. Indeed, some performance vehicles (e.g., BMW M-series vehicles, Chevrolet Camaro and Corvette, and Mercedes-AMG vehicles) allow drivers to switch to a HUD interface displaying sporty driving-specific contents, such as shift light (indicating that the vehicle's best performance level has been reached to shift to higher gear), lateral acceleration (G-force), and lap and race timers. Similarly, HUD interfaces specific to other driving modes could be developed. For example, a HUD interface displaying instantaneous fuel consumption rate (Table 3.13), or gear shift indicator for fuel efficiency would support economical driving.

Wayfinding

Many participants commented that HUD navigation information items were useful when finding their way especially in complex roads or new/unfamiliar places (Tables 3.5, 3.9 and 3.10). Wayfinding requires parallel visual information processing of navigation information and road scene ahead, and, thereby, demands considerable attentional resources and working memory processes (Montello and Sas 2006). HUD seems to lighten such cognitive demands, by reducing information access costs for the parallel processing. Indeed, HUD was regarded as the best medium for displaying turn-by-turn navigation (Green 1996), and HUD navigation showed lower reaction times, better awareness of surroundings, less navigational errors, and higher preference ratings than HDD navigation (Srinivasan and Jovanis 1997; Burnett 2003; Jose, Lee and Billinghurst 2016).

Some survey participants wanted detailed navigation instructions for complex routes (Table 3.5). Also, a few wanted a more realistic and understandable HUD interface design that utilizes visual elements resembling the real road environment and objects in it (Tables 3.5 and 3.9). Future research studies are needed to investigate how the level of details and that of realistic quality of the interface affect the understandability of a HUD-based navigation system and the relevant task performance. A detailed/realistic HUD interface for navigation may provide advantages over a simple/abstract one in terms of understandability; yet, it may cause side-effects, such as visual clutter and driver distraction (Lee et al. 2014).

Sign/warning detection

The survey results indicated that HUD facilitated timely detection of road sign (Tables 3.4 and 3.9) and vehicle maintenance warning (Tables 3.6 and 3.13). This reflects the main advantage of HUD over HDD, that is, the faster detection of visual information to better support situation awareness (Sojourner and Antin 1990; Liu and Wen 2004; Charissis and Papanastasiou 2010). HUD would be a good medium for presenting time-critical information items in future vehicles, such as take-over request in automated driving (Cha and Park 2006; Politis, Brewster and Pollick 2015; Walch et al. 2015).

As for maintenance warning, several participants responded that they wanted to obtain details through HUD, such as additional explanations and suggested solutions (Table 3.6). This user need seems to be in line with the existing design recommendation that in-vehicle warning symbols, despite the advantages of fast recognition and language independence, need to be supplemented with textual information or action instructions to be used effectively and prevent misunderstanding (Baber and Wankling 1992; ISO/TR 16352:2005). Despite the utility of additional detailed information, however, research is needed to develop display methods/interfaces that would safely and effectively deliver such additional information as presenting much information on HUD is likely to be unsafe or undesirable in many driving situations (Stevens et al. 2002; Charissis and Papanastasiou 2010). Also, individual drivers' different preferences need to be considered in determining the levels of detail for presenting the information (ISO 9355-1:1999).

Audio player control

The survey results revealed that one of the main functions of commercial automotive HUD systems was to support audio player control (Table 3.8). This indicates that listening to music and other audio contents, although not pertaining to the primary driving tasks, is an important element of the overall driving experience (Knobloch and Zillmann 2002).

Future studies may explore new HUD interface designs for audio player control. In doing so, interface designs from other domains, for example, the 'Cover Flow' interface in desktop and mobile products for visually flipping through albums/tracks, could be tested for HUD implementation, and be compared with the existing scrolling list interface. HUD may also be used to present other information related to the audio player system, such as volume level (Table 3.8), progress bar, lyrics, or playing mode (e.g., shuffle, repeat). The necessities/utilities of such HUD features need to be examined.

<u>Accuracy issues of HUD information items</u>

The survey results revealed two information accuracy issues in the existing HUD systems. One is the inaccuracy of HUD navigation/traffic information, resulting from the delayed updates and poor wayfinding performance of the on-board navigation system (Tables 3.4, 3.5, 3.9 and 3.10). Since the existing Original Equipment Manufacturer (OEM) HUD systems display what has been already stored in the on-board navigation systems, these issues should be addressed by their regular/automatic updates and continual performance improvements. Alternatively, HUD systems could utilize information from navigation applications of mobile devices or actual roadway signs. A camera-based traffic sign recognition system would be needed to utilize roadway signs as a source of information (Grimm 2013). Indeed, some OEM HUD systems (e.g., BMW, Jaguar, Land Rover, Mercedes-Benz, and Volvo) can display speed limit and no overtaking signs detected by such recognition system. Future HUD systems may be designed to combine/fuse information from multiple sources to improve the accuracy of the presented information.

The other issue is the time lag that exists in presenting current speed, cruise control status and RPM on the HUD in real-time (Tables 3.3, 3.7 and 3.12). Lagged systems are known to create considerable stress for the operator and degrade task performance due to the unavailability of feedback from earlier actions to help plan the current action and the increased cognitive demands required to anticipate the future state (Wickens et al. 2013; Scholcover and Gillan 2018). Considering that the commented information items are directly relevant to the primary driving tasks, the latency should be reduced not to adversely affect task performance, nor to make drivers look down to HDD instead.

Individual- and context-specific HUD information needs

The survey results overall indicated that information needs of HUD users varied significantly from one user to another, and, also from one context to another (Tables 3.4, 3.11, 3.12 and 3.13). Some of the survey participants responded that they wanted to be able to decide what to display with their HUD systems and also specify the conditions for turning on/off certain HUD information items (Tables 3.4, 3.9, 3.11 and 3.12). Some information items were even considered unnecessary because of information redundancies (easily obtainable from HDD or auditory signal), individual driving styles, and concerns about clutters and/or obscurations (Tables 3.7, 3.8, 3.10, 3.11, 3.12 and 3.13).

One way to address the individual- and context-specific nature of the user information needs is to provide customizable features to HUD systems. While some existing HUD systems can be customized, users are only allowed to turn on/off only a certain part of the entire information provided or switch between several sets of information items predetermined by the manufacturer (e.g., GM [Buick, Cadillac, Chevrolet, GMC], Honda, Mercedes-Benz, Toyota) – they are not allowed to turn on/off each information item one by one. Future HUD systems may need to be more flexible to better address the individual- and context-specific HUD information needs.

Despite the likely benefits of customizable HUD systems, however, basic research needs to be conducted to ensure safety and utility of such systems. Some research questions are as follows: 1) User-customization of a HUD system should be restricted within certain safety limits so as not to compromise driving safety (Stevens et al. 2002; Yayici 2014). How can the safety limits on the amount of information displayed by an automotive HUD system be determined for each individual driver? Can drivers accurately determine the safety limits for themselves? 2) Can users determine HUD information items they need and/or specify the display-on/off conditions? In other words, do they know what they need/want and when? If not, how can a HUD system discover/learn the user's information needs/wants? 3) How can a HUD system be customized in an easy and efficient manner? What is the user interface that best assists the drivers in specifying their personal settings?

Visibility issues of HUD images

Some participants suggested using various colors or large-sized images for improving the visibility of HUD images (Tables 3.3, 3.5, 3.6 and 3.8). Visibility is a critical human factors design issue in developing automotive HUDs, and, previous studies have provided relevant design suggestions (Inuzuka, Osumi and Shinkai 1991; Ahlstrom and Kudrick 2007; Choi et al. 2013; Park et al. 2016).

Some research questions concerning the visibility of HUD images include the following: 1) Visibility of HUD images would deteriorate with visual complexity of the background, especially with dynamic interference from the outside road environment (Ward and Parkes 1994; Stevens et al. 2002). How can HUD images be adaptively displayed to be visible in all of the potential viewing conditions? 2) Large-sized HUD images can add to visibility, but at the same time, compromise compactness of a display (ISO/TR 16352:2005). How can a proper balance for their size be achieved? 3) Visibility issues would require careful consideration of individual differences. Some OEM HUD systems (e.g., Genesis, Hyundai, KIA) allow users to choose from three font colors (white, orange and green) and three font sizes (small, medium and large) for displaying current speed in order to accommodate the needs/preferences of different drivers. How much adjustability is required to achieve a high level of population accommodation in displaying each major information item?

Visual aesthetics of HUD interfaces

A few participants wanted more appealing visual aesthetics for automotive HUD interfaces (Tables 3.11 and 3.12). Appealing visual aesthetics is in general known to positively affect usability, user performance, or overall user experience (Tractinsky, Katz and Ikar 2000; Moshagen, Musch and Göritz 2009; Sonderegger and Sauer 2010; Reppa and McDougall 2015). Aesthetic preference varies greatly across different individuals – age, gender, personality, cultural background and experiences are known to affect the responses to aesthetics (Crilly, Moultrie and Clarkson 2004; Sonderegger and Sauer 2010). Research studies are needed to understand the aesthetic preferences of the automotive HUD user population.

HUD location and layout issues

A few participants commented that they wanted current speed to be displayed on the driver's normal line-of-sight (Table 3.3). This comment seems reasonable because displaying the high-priority information close to the sightline is generally recommended (Green et al. 1994; Stevens et al. 2002; ISO/TR 16352:2005; Bhise 2011). However, it has also been recommended that HUD image should be slightly away from the direct line-of-sight to avoid cognitive capture or visual obscuration (Sojourner and Antin 1990; Ward and Parkes 1994; Watanabe et al. 1999; Stevens et al. 2002; Horrey and Wickens 2004; Wittmann et al. 2006; Bergman 2011). The trade-offs between these two design considerations should be carefully studied in future research efforts.

Additionally, there was an issue of multiple information items being displayed overlapped with one another (Table 3.13), which needs to be resolved to avoid potential problems, such as driver distraction and/or information loss. If multiple information items are to be presented simultaneously, their relative priority may be considered to optimize their layout – for example, by emphasizing the higher-priority items to be more visually accessible, without being overlapped/blocked by others (ISO/TR 16352:2005; SAE J2831 2012). Alternatively, allowing drivers to deactivate any or all of the items presented on HUD on an ad hoc basis (SAE J2831 2012) could, to some extent, address the issues of information items being overlapped.

Lastly, many commercial HUD systems currently allow users to adjust the location of the displayed items as a whole, but not individually. An additional adjustability feature for controlling the location of each displayed item may help better accommodate drivers with different preferences (Guo et al. 2014).

3.4 Concluding Remarks and Future Research Directions

The current study surveyed experienced automotive HUD users to determine the perceived importance of the twenty-two HUD information items displayed by the existing commercial automotive HUD systems, and examine the contexts of use and the user-perceived design improvement points for high-priority information items. The study results indicated that the information items varied greatly in perceived importance, and current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status, and low fuel warning were of highest importance. Also, participants' prior experience of using an information item was found to greatly impact the average importance rating, suggesting that information items' importance must be evaluated by those with sufficient information item use experience. For eleven high-priority HUD information items (in terms of the perceived importance and number of participants with prior information item experience), design implications were derived from the survey responses to the usage contexts and design improvement points. They may contribute to improving the existing automotive HUD systems in both the system functions and the interface/interaction design.

Some future research directions are provided here:

For many of the information items considered in this study, the number of participants with prior information item experience (N_exp) was small. Further studies with large N_exp are needed to provide more accurate estimates of their importance and more sufficient and/or different responses to their usage contexts and design improvement points.

Also, the current study results pertain to the existing commercial automotive HUD systems. As the automotive HUD systems evolve along with the advanced driver-assistance systems (ADAS) and in-vehicle information systems (IVIS), and, also the autonomous vehicle technology, the contexts of system use and the users' wants and needs will change accordingly. Thus, continuous follow-up research will be necessary to update the current study results. For example, Cha and Park (2006), Politis, Brewster and Pollick (2015), Walch et al. (2015), Wulf et al. (2015) and Kim, Yoon and Ji (2016) proposed HUD information items for automated vehicles; research studies would be needed to examine such newly proposed information items' importance, usage contexts, design improvement points.

Lastly, the current study utilized the written survey method for data collection. While written surveys have been used to understand product use practices and user wants and needs in a variety of product design contexts (Rubin and Chisnell 2008; Goodman, Kuniavsky and Moed 2013), the UX literature generally emphasizes the importance of on-site observations of users and product use practices in natural settings (Hartson and Pyla 2012; Goodman, Kuniavsky and Moed 2013). Additional studies based on on-site observations may provide further design insights.

Chapter 4

A Driving Simulator Study on Camera Monitor System (CMS) Display Layouts

4.1 Research Methods

4.1.1 Equipment

A fixed-base three-channel driving simulator consisting of a vehicle interior mock-up of a commercial sedan and display equipment was used in this study (Figure 4.1). The vehicle interior mock-up was comprised of a driver's seat, a steering wheel, gas and brake pedals and a gearshift, all of which were adjustable and were mounted on a base frame of 1000mm × 1600mm (width × length) constructed with aluminum extrusion profiles. The display equipment was comprised of three 42-inch LED monitors, which were installed around the front of the vehicle mock-up to provide an immersive driving environment with a horizontal forward field of view (FOV) angle of 183.6° . A driving simulation software program UC-win/Road Ver.10

(Forum8) was used to develop the virtual driving scenario, run the experiment and measure driving performance. The Dikablis head-mounted eye tracking system (Ergoneers) was used to record each participant's eye and head movement.

Figure 4.1: Three-channel driving simulator

4.1.2 Design Alternatives

This study comparatively evaluated four alternative mirror/display arrangements: Control, Design A, Design B and Design C (Figure 4.2).

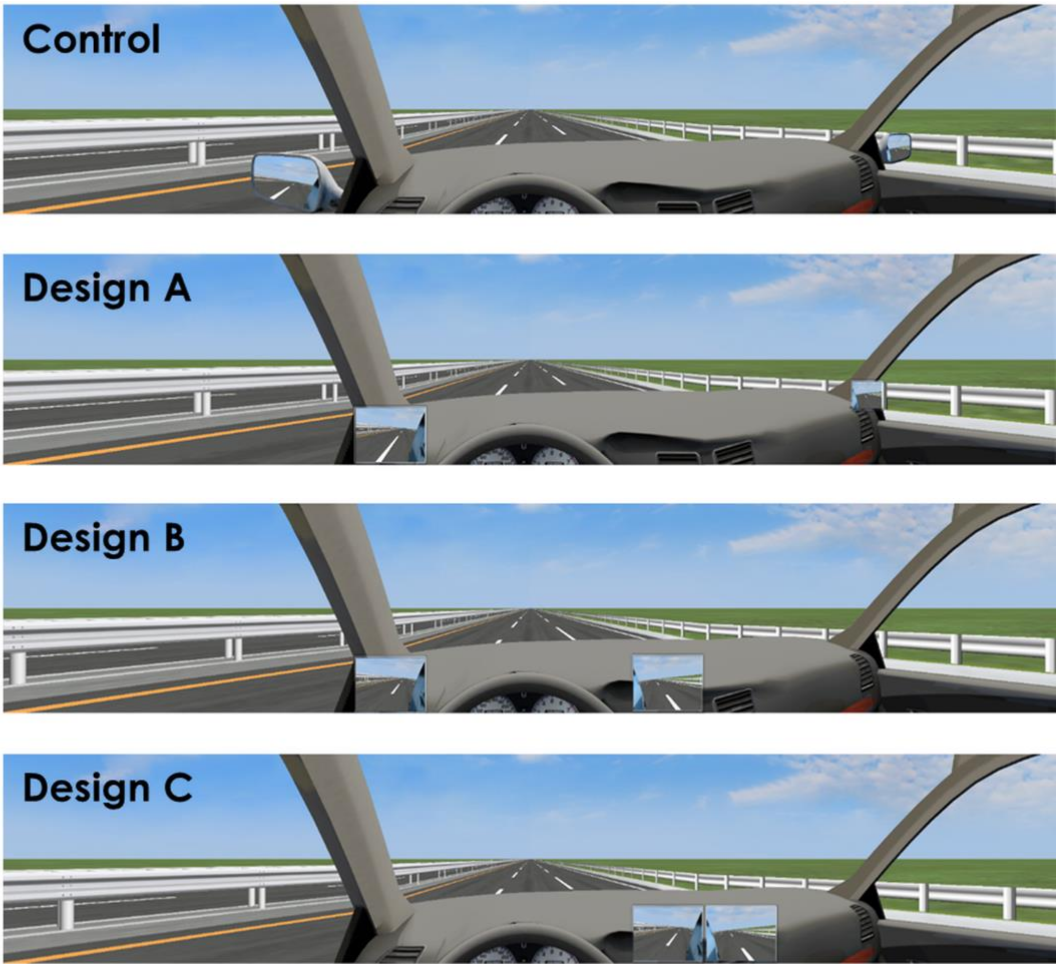

Figure 4.2: Four alternative arrangements comparatively evaluated

Control was the conventional side-view mirror arrangement. The other three (Designs A, B and C) represented different arrangements of two in-vehicle side-view displays – in these arrangements, the side-view mirrors were removed. The three CMS side-view display layouts, Designs A, B and C, were developed considering the designs examined in the previous human factors studies on CMS (Mohamed Ali and

Fatin Bazilah 2014; Large et al. 2016; Schmidt et al. 2016) and the existing ergonomics design guidelines for in-vehicle visual displays (Green et al. 1994; Stevens et al. 2002; Bhise 2011). The three layouts differed from one another in terms of required driver eye gaze travel distance and compatibility with driver expectation.

In Design A, the side-view displays were located inside the car nearby the conventional side-view mirrors; it had the advantage of being similar to the conventional side-view mirror arrangement, and, thus, being concordant with the driver's expectation. This design had been implemented in some concept cars such as Volkswagen XL1 (Lassa 2011). Although the two side-view displays were still distant from each other and also distant from the driver's normal line-of-sight, the design provided slight reductions in the eye gaze travel distance compared to Control. In Design B, the side-view displays were located on the dashboard at each side of the steering wheel. Thus, compared with Design A, the side-view displays were closer to each other and also to the driver's normal line-of-sight. In Design C, the two side-view displays were joined together and located on the center fascia resulting in the minimum eye gaze travel distance.

Taken as a whole, as it goes from Control to Design A to Design B to Design C, the two side-view displays get closer to each other and require less eye gaze travel distance. On the other hand, as it goes from Design C to Control, the side-view display layout would become more conforming to the driver's previous experience and expectation (or mental model), better satisfying the fundamental human factors 'compatibility' principle (Sanders and McCormick 1993; Wickens et al. 2013).

Since the current study was primarily focused on where to place the side-view displays inside the vehicle, each display was designed to provide the exactly same view as that of the corresponding side-view mirror. Consequently, potential benefits of CMS, such as enlarged visual fields or improved vision, were not explored in this study. Also, the side-view displays of Designs A, B and C and the exterior mirrors of Control were assumed to be of the same size. All side-view displays were rectangular in shape.

4.1.3 Driving Scenario and Experiment Task

The research objectives of the current study were to investigate the effects of CMS side-view display layout design on the driver information processing (driving performance and safety) and the physical demands of driving in a dangerous driving scenario. Considering the study objectives, this study devised a time- and safety-critical driving scenario and an experiment task that required the driver to rapidly check both side-view mirrors/displays to assess the situation behind/beside the vehicle and choose an adequate response. The experiment task imposed non-trivial physical demands on the driver's eye and head musculature in addition to cognitive demands.

At the onset of each experiment task trial, the participant's vehicle was generated on the second lane in a three-lane highway. The vehicle speed was fixed at 100 km/h throughout the trial – thus, the participant used only the steering wheel without operating the pedals. The participant was instructed to stay in the second lane. Then, at a random time, an obstacle appeared 100 m ahead of the participant's vehicle where the time taken for head-on collision was only 3.6 s. Simultaneously with the obstacle, two virtual vehicles were created 5 m and 15 m behind the participant's vehicle – one in the first lane and the other in the third lane. The assignment of the closer and more distant vehicles to the first and the third lane was randomized for each trial. Both virtual vehicles moved forward at a constant speed of 105 km/h, where the time taken for the participant's vehicle to be overtaken was 3.6 s for the closer vehicle and 10.8 s for the more distant one, respectively. The participant was instructed to examine both side-view mirrors/displays, judge the distances from the virtual vehicles (the closer rear vehicle looks bigger through the side-view mirrors/displays) and then make a safe lane change to the lane with the more distant virtual vehicle as quickly as possible so as to avoid the imminent collision with the obstacle ahead as well as the closer virtual vehicle behind. The entire process of decision making, response selection and execution had to be completed within 3.6 s given the fixed speeds of the vehicles. Once the participant's vehicle safely avoided the obstacle, the driving task trial was automatically reset, and the participant's vehicle was generated on the second lane again for the next trial. Figure 4.3 illustrates the driving scenario from the top view.

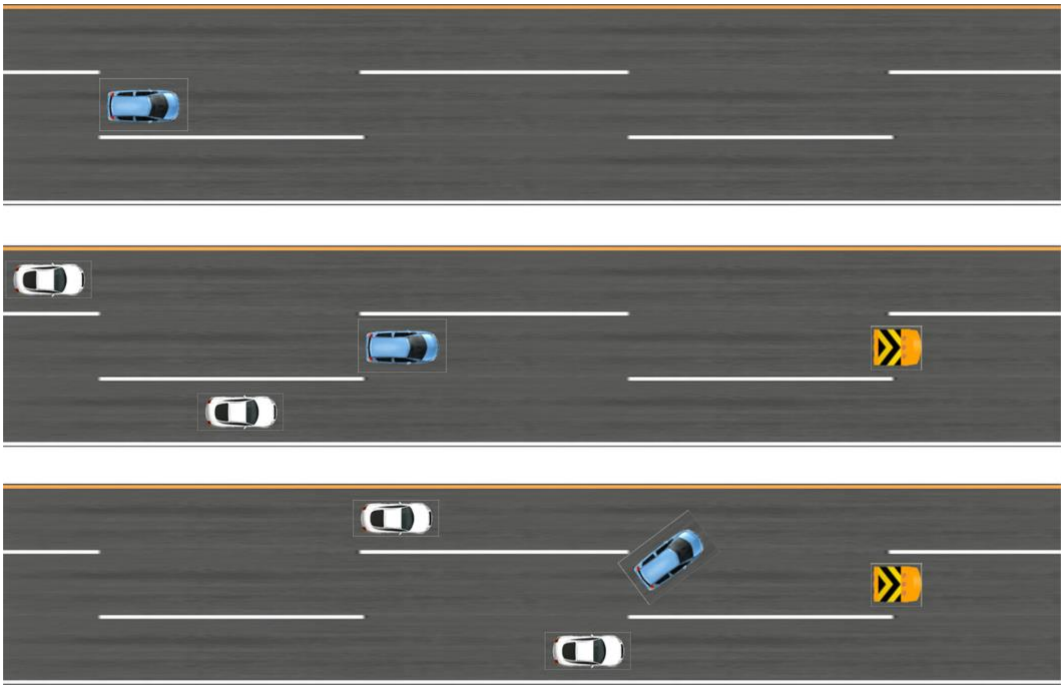

Figure 4.3: Task scenario

The scenario and associated task above were designed to serve as a generic representation of dangerous driving situations that require rapidly gaining situation awareness through the side-view mirrors/displays and making adequate lane change maneuvers to avoid imminent collision. Such situations include: sudden stop of a vehicle ahead, abrupt cut-in of a vehicle from an adjacent lane, unexpected appearance of an obstacle ahead (e.g., pedestrian or animal) or urgent lane change at high-speed (e.g., at highway exit or entrance).

4.1.4 Participants and Experimental Procedure

A total of 22 participants (19 males and 3 females) participated in this driving simulator study and their mean age and driving experience were 27.5 (range, 24-32; standard deviation, 2.13) and 5.5 (range, 1-11; standard deviation, 3.17) years, respectively. Before the start of the experiment trials, enough training session was provided to the participants so that they became familiar with the driving simulator, scenario, task and each of the four alternative mirror/display arrangements. For each of the four design alternatives, each participant, with the Dikablis eye tracker (the head unit of the eye-tracking system) mounted on the head, performed five consecutive experiment trials. The presentation order of the four design alternatives was randomized for each participant. The data collection protocol had been approved by the Institutional Review Board of Seoul National University.

4.1.5 Experiment Variables

The independent variable of the study was design (spatial arrangement of side-view mirrors/displays), which had four levels: Control and Designs A, B and C. As for the dependent variables, a set of five information processing (driving performance and safety) measures and three physical demand measures were employed.

Among the five information processing measures were two objective and three subjective measures. The objective measures were: eye-off-the-road time, and response time for the onset of maneuvering. The subjective measures were: perceived workload, preference and perceived safety ratings.

The eye-off-the-road time was defined as the time spent looking away from the road during each experimental trial and was determined utilizing the eye tracking system. Before calculating the eye-off-the-road time, preprocessing of the eye tracking data was performed based on International Standard ISO 15007-2:2014 as follows. First, blinks (short moments in which the eye is closed by the eyelid) were eliminated; if a glance is divided by a 'normal blink' (no pupil recognition) shorter than/equal to 300ms, the glance was treated as a continuous glance (not two). Then, 'fly throughs' (very short glances captured when the eye is making a saccade) were eliminated; such an artifactual fixation shorter than 120ms was treated as part of a saccade (not a short fixation).

The response time was computed as the time taken from the appearance of the obstacle to the onset of the driver's lane changing maneuver. The onset of the lane changing maneuver was defined as the time when the participant started turning the steering wheel and was identified by the angle and angular velocity of the steering wheel recorded in the log data from the driving simulation software program.

As mentioned earlier, the participants performed the lane changing task trial five times in a row for each of the four design alternatives. Thus, for each of these two objective measures, the mean of the five data points was computed and used for subsequent analyses.

After finishing the five trials for each of the four design alternatives, the participants completed the NASA Task Load Index (TLX) questionnaire (Hart and Staveland 1988) to assess the workload they experienced during the experiment and also performed preference and safety ratings on a ten-point scale.

The three physical demand measures were spread of eye gaze positions, spread of head positions and perceived physical demand. The first two measures pertained to eye and head movements, respectively, and the third is concerned with subjective perception of the overall physical demand. Each physical demand measure is described in detail in the following.

Spread of eye gaze positions was employed as a measure of physical demands imposed on the oculomotor system. For each participant and each design alternative, it was calculated as the standard deviation of the x-coordinates of the gaze-points during the five consecutive trials, in the coordinate system of the scene-camera image (Chapman and Underwood 1998; Crundall and Underwood 1998; Alberti, Shahar and Crundall 2014; Kasneci et al. 2014; Mackenzie and Harris 2017). A larger spread of eye gaze positions means wider horizontal eye movements. The spread of eye gaze positions in pixels was converted into degrees, a visual angle measured from the head. In the Dikablis eye tracking system, the coordinate system of the scene-camera image is given as an area of 1920x1080 pixels with the origin in the top left corner. The eye tracker camera lens afforded horizontal FOV of 77°; thus, a horizontal movement of 1 pixel equals 0.04° (77°/1920 pixels).

Spread of head positions was employed as a measure of the physical demands imposed on the musculature for head movement, which was computed in a way similar to the spread of eye gaze positions. The eye tracker was mounted on the participant's head, and, thus, a head movement naturally involved a positional change of the coordinate system of the scene-camera image – a torso movement also could result in the movement of the coordinate system, but the participants' torso movement was negligible during the experiment trials, and, therefore, the positional change of the coordinate system could be considered as mostly resulting from head movement. The spread of head positions was computed utilizing a reference point, which was detected by the camera throughout each experiment trial. The coordinate change of the reference point reflected the positional change of the coordinate system of the scene-camera image, and, thus, that of the head position. The Dikablis eye tracking system used printed quick response (QR) code markers as reference points. One of the QR code markers placed at a location detectable throughout the entire recording was selected as the reference point for quantifying the positional change of the coordinate system. The spread of head positions was computed as the standard deviation of the x-coordinates of the reference point. Again, the pixel-to-degree unit conversion was conducted.

Perceived physical demand, as an overall measure of the physical demands associated with using the side-view mirrors/displays, was obtained through subjective ratings of physical demands. After finishing the five consecutive task trials for each design alternative, the participants assessed the physical demands they perceived during the experiment trials on a 100-point scale with the endpoints 'Low' (0) and 'High' (100). The question given to the participants was 'How physically demanding was the task?'

The spread of eye gaze positions and that of head positions along the vertical axis (i.e., the standard deviations of the y-coordinates of the gaze-points and the reference points) were not considered in this study. This was because there was no difference in the vertical positions of CMS displays across the four design alternatives. A pre-investigation verified that the vertical spread of eye gaze positions and head positions did not change across the layouts.

4.1.6 Statistical Analyses

A one-way repeated measures ANOVA was conducted to test the effect of the independent variable (display layout design) on each dependent variable. For each ANOVA, Mauchly's test was performed to assess sphericity of data. In cases where sphericity was violated, the degrees of freedom were corrected – the Greenhouse-Geisser correction was used when the Greenhouse-Geisser estimate of sphericity (ε) was less than 0.75; otherwise, the Huynh-Feldt correction was used (Field 2009). If an ANOVA identified a significant effect, post-hoc Bonferroni multiple pairwise comparisons were conducted. Bonferroni correction was made to reduce the risk of Type I errors. All statistical tests were conducted at an alpha level of 0.05 using SPSS 21.0 (SPSS Inc., Chicago, USA).

4.2 Effects of CMS Side-view Display Layout Design on the Driver Information Processing

4.2.1 Results

The statistical analyses results showed that the design factor (spatial arrangement of mirrors/displays) significantly affected all of the five dependent measures (eye-off-the-road time, response time, perceived workload rating, preference rating and perceived safety rating) with each p-value less than 0.001. For each of these dependent variables, the mean and standard deviation of each design alternative are shown in Figures 4.4-4.8 with asterisk indicating the statistical significance in the post-hoc Bonferroni multiple pairwise comparisons.

The results of the ANOVA and post-hoc Bonferroni multiple comparisons on eye-off-the-road time (Figure 4.4) indicated that all the three in-vehicle side-view display layouts examined in this study, that is, Designs A, B and C, resulted in significantly shorter mean eye-off-the-road time than the conventional mirror system (Control). Also, Designs B and C were found to be superior to Design A. Designs B and C did not significantly differ from each other in the mean eye-off-the-road time.

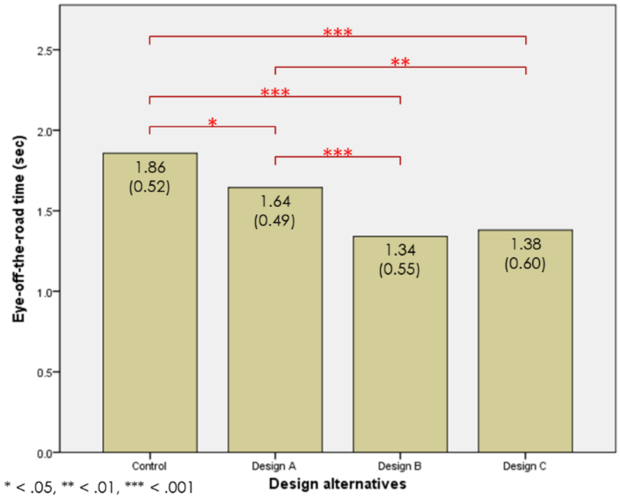

Figure 4.4: Bar graph for eye-off-the-road time with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

Identical results were found for the response time measure (Figure 4.5).

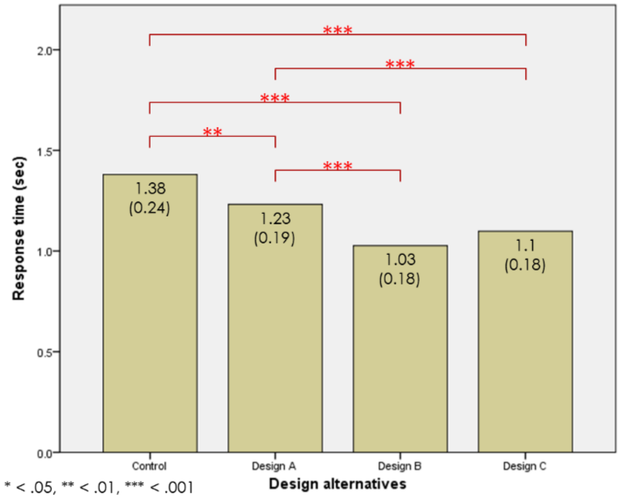

Figure 4.5: Bar graph for response time with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

Also for perceived workload (Figure 4.6), all three display layouts were better than Control, and Design B was superior to Design A; however, Design C did not significantly differ from Design A and was inferior to Design B.

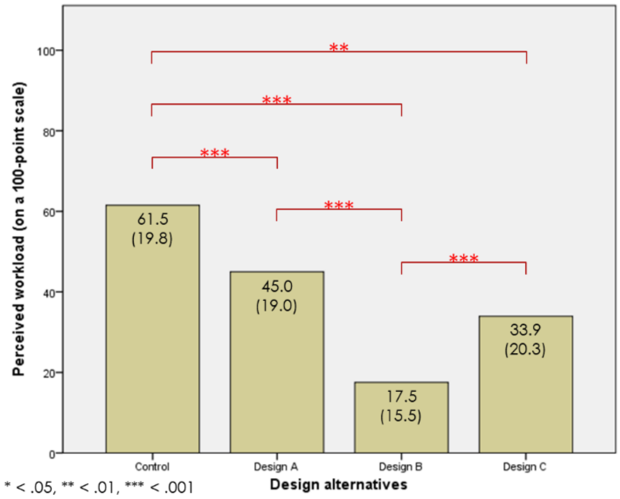

Figure 4.6: Bar graph for perceived workload with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

As for preference and perceived safety (Figures 4.7 and 4.8), Design B consistently showed the best results followed by Design A, and, then, Control; however, Design C did not significantly differ from Control or Design A and was inferior to Design B.

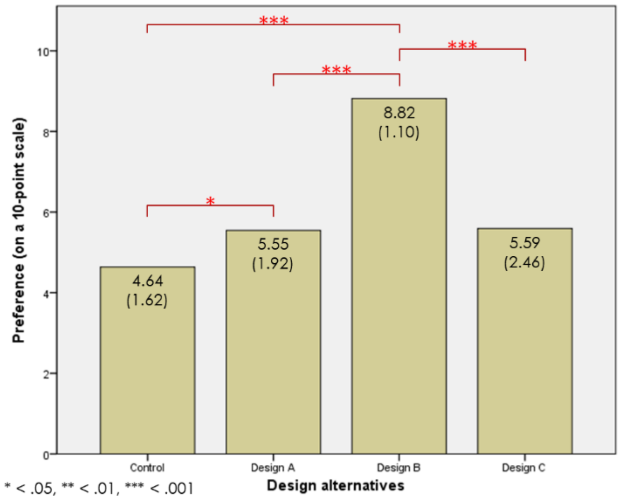

Figure 4.7: Bar graph for preference with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

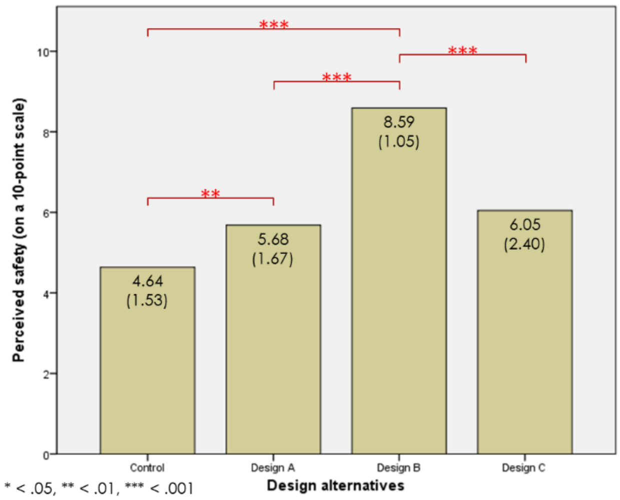

Figure 4.8: Bar graph for perceived safety with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

Meanwhile, in all of the experiment trials, the driver error of incorrect lane changing (to the lane of the closer virtual vehicle) occurred only twice – both for the conventional mirrors condition (Control).

4.2.2 Discussion

The current study comparatively evaluated three different CMS side-view display layouts and the conventional side-view mirror arrangement (Figure 4.2) in a driving simulator experiment. The simulator experiment employed a time- and safety-critical task scenario - making a lane change to avoid an imminent collision. Major study findings are recapitulated below:

- Control was the worst design in all of the five dependent measures (eye-off-the-road-time, response time, perceived workload rating, preference rating and perceived safety rating). Incorrect lane change errors occurred only for Control.
- Design A was better than Control and worse than Design B, consistently across the five dependent measures.
- Design B was the best in all of the five dependent measures.
- Design C, together with Design B, was the best design in the eye-off-the-road time and the response time – it should be noted that Design C was not significantly better than Design B in these two objective measures. Design C was not the best design in any of the three subjective measures (perceived workload, preference and perceived safety ratings) – it was

consistently worse than Design B across the subjective measures; furthermore, it did not significantly differ from Design A in all the subjective measures, nor did it differ from Control in the preference or perceived safety.

The study results seem interpretable largely in terms of eye gaze travel distance needed for conducting the experiment task and its effects on information processing. The experiment task required the driver to look at the road ahead and also check both of the two side-view mirrors/displays (hereafter, simply side-view displays). The inter-distances between the three gaze points, that is, the normal line-of-sight (looking at the road ahead) and the two side-view displays, affect the eye movement time during the task, and, therefore, would naturally impact eye-off-the-road time, response time, and, other dependent measures.

The inter-distances are also thought to impact the dependent measures through affecting the difficulty of the information processing involved in the experiment task. The task required each participant to check both side-view displays and integrate the information from them to judge the relative distances from his/her own vehicle to the two vehicles in the adjacent lanes. In such task, a large inter-distance between the two side-view displays, which precludes simultaneous/near-simultaneous processing of visual information, demands retaining information in working memory – the driver must process the visual information from one display, retain it in working memory while moving the eye gaze to view the other display, and, finally, integrate the information from the two displays to judge the relative distances. Increased inter-distance between the displays increases the time duration of working memory information retention, and, this in turn would increase the task difficulty due to the transient characteristics of working memory (Wickens et al. 2004, 2013).

In addition to working memory information retention, a large inter-distance (and, thus, a large time gap) between the side-view displays inevitably demands future system state prediction - in order to make a correct judgment on the relative distances to the vehicles in the adjacent lanes, the driver must compare the information from the second display with the predicted, current state of the vehicle seen earlier from the first display. An increase in the time gap between the first and the second display increases the prediction's difficulty. Future system state prediction through mental simulation imposes heavy cognitive demands on working memory, and, is known to be difficult in general (Wickens et al. 2004).

With the above considerations, it is thought that bringing the three gaze points close to one another is beneficial for the experiment task. Especially, the three gaze points substantially closer to one another than those of the conventional mirror system (as in Design B or Design C) would allow the visual information to be processed simultaneously or near-simultaneously. This minimizes the eye movement time and eliminates the needs for working memory information retention and future system state prediction. This in effect allows the driver to perform the experiment task using 'easily accessible' knowledge in the world rather than knowledge in the head. The use of 'knowledge in the world' is known to increase the ease and accuracy of information processing (Wickens et al. 2004; Norman 2013).

Locating the gaze points in the close proximity also seems advantageous when considered in light of the ergonomics display design principles: first, it is consistent with the well-known display-control layout design principles of functional grouping, sequence-of-use and priority of information (Sanders and McCormick 1993; Stevens et al. 2002; Wickens et al. 2004; Bhise 2011). The functional grouping principle states that functionally related components should be grouped in the same location. The sequence-of-use principle states that sequentially used components should be so arranged as to make good use of such patterns. According to the priority of information principle, the visual displays showing high priority information should be located close to the driver's normal line-of-sight. The three gaze points are functionally-related and also sequentially used during the experiment task considered in this study. Also, the two side-view displays are of high priority not only in the context of the experiment task of the current study but also in general driving situations. Second, the two side-view displays, if located close to each other, may function as a configural (object) display. A configural display combines different pieces of information into a single object and may facilitate information integration and pattern perception through providing a useful emergent feature (Sanders and McCormick 1993; Wickens et al. 2004). The two side-view displays when located in the closest proximity (as in Design B or Design C) may give rise to a few 'whole' visual patterns each of which directly indicates a safe direction for lane change without requiring further information processing. Making use of such patterns could substantially reduce the driver's cognitive workloads. Admittedly, the idea of side-view displays closely located to each other functioning as a configural display is a conjecture and needs to be tested in future research efforts.

Overall, the above line of reasoning leads to the prediction that the inter-distances between the gaze points are positively correlated with the number of incorrect lane change errors, eye-off-the-road-time, response time and perceived workload rating, and, are negatively correlated with preference and perceived safety ratings. In fact, this prediction mostly conforms to the study results - as mentioned earlier, incorrect lane change errors occurred only for Control which had the largest total inter-distance between the gaze points. Also, the three designs, Control, Design A and Design B, exhibited statistically significant mean differences conforming to the prediction for all of the five dependent measures (Figures 4.4-4.8). However, the prediction did not perfectly match the observations from the study. Design C with the smallest combined inter-distance was not the best design alternative - again, it was not significantly different from Design B in the eye-off-the-road time nor in the response time and it was worse than Design B in each of the three subjective measures. Moreover, it did not show a significant advantage over Design A in the perceived workload rating and was not better than any of the other design alternatives in the preference nor in the perceived safety rating.

The reasons Design C did not show the best results despite the smallest combined inter-distance are not entirely clear. Nonetheless, some possible explanations can be suggested: first, the observation that Design C was not significantly better than Design B in the two objective measures (eye-off-the-road-time and response time) may be because in Design B, the two side-view displays were close enough to each other and to the normal-line-of-sight, allowing the visual information to be simultaneously or near-simultaneously processed. Consequently, further reduction in the inter-distances between the gaze points, as accomplished in Design C, could not result in any improvement in the eye movement time. Twelve out of the twenty-two participants indeed commented that Designs B and C enabled simultaneous visual information processing, during the post-experiment interview.

Second, Design C seems to contain aspects that violate compatible spatial relationships (Sanders and McCormick 1993; Wickens et al. 2013). Design C has the two side-view displays side-by-side with the left side-view display on the left and the right side-view display on the right. These relative positions are natural and are compatible with the driver's expectation. However, with respect to the driver (the egocentric axis) and the steering wheel, the left side-view display is located in the right side, which represents an incongruent spatial relationship (Esser 2016) - this is indeed a consequence of the design decision to minimize the inter-distance between the two side-view displays. Umiltà and Liotti (1987) showed that not only the relative positions of two stimuli to each other but also their positions with respect to the egocentric axis can give rise to stimulus-response compatibility effects. The non-compatible design element in Design C could adversely affect information processing and is thought to, at least partially, explain the reason Design C was not better than Design B in either of the two objective dependent measures and was not good in terms of the subjective measures - according to Sanders and McCormick (1993), greater degree of compatibility is accompanied by less recoding to process information, faster learning, faster response times, fewer errors, less mental workload, and more user satisfaction. Related to the non-compatible design element of Design C, it should be noted that United Nations Regulation No. 46 (United Nations Economic Commission for Europe 2016) requires the CMS images of the left and right side fields of view to be presented to the left and right to the ocular reference point, respectively. The study findings regarding Design C empirically support this UN regulation. It also seems to corroborate the finding of Umiltà and Liotti (1987) mentioned above with empirical data collected from a realistic work task scenario. Again, Design C, when considered in comparison with Design B, is thought to sacrifice compatibility for minimizing eye gaze travel distance. As can be seen from the study results, such trade-offs would have to be carefully studied in order to make a correct design decision.

4.3 Impacts of CMS Side-view Display Layout Design on the Physical Demands of Driving

4.3.1 Results

The ANOVA results showed that display layout design significantly affected all of the three dependent measures (spread of eye gaze positions, spread of head positions and perceived physical demand) with p-values less than 0.001. For each of these dependent variables, the mean and the standard deviation of each design alternative are shown in Figures 4.9–4.11 with asterisks indicating statistical significance in the post-hoc Bonferroni multiple pairwise comparisons.

As for the spread of eye gaze positions (Figure 4.9), Control showed the largest mean (i.e., the largest side-to-side eye movement), followed by Design A, Design C, and Design B.

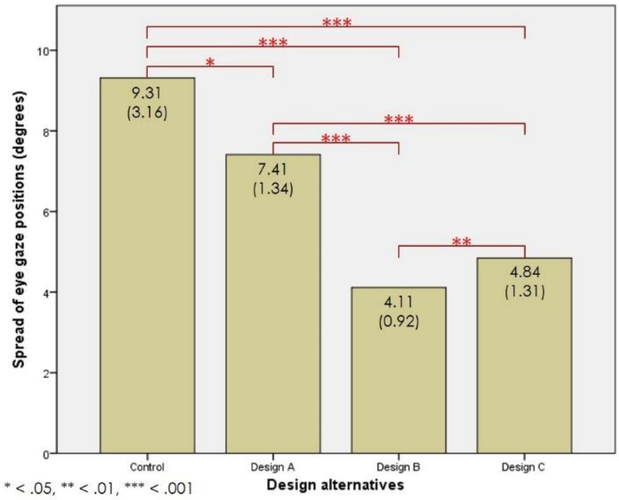

Figure 4.9: Bar graph for spread of eye gaze positions with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

As for the spread of head positions (Figure 4.10), Control and Design A had larger means (i.e., larger side-to-side head movement) than Designs B and C. Control and Design A did not significantly differ from each other, nor did Designs B and C, in the mean spread of head positions.

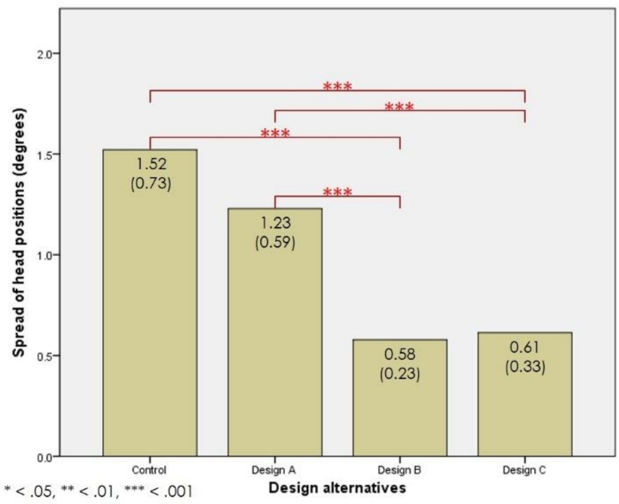

Figure 4.10: Bar graph for spread of head positions with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

The results for the perceived physical demand (Figure 4.11) showed the same pattern as the spread of head positions – Control and Design A resulted in larger mean perceived physical demand than Designs B and C. Control and Design A were not significantly different from each other, nor were Designs B and C, in the mean perceived physical demand.

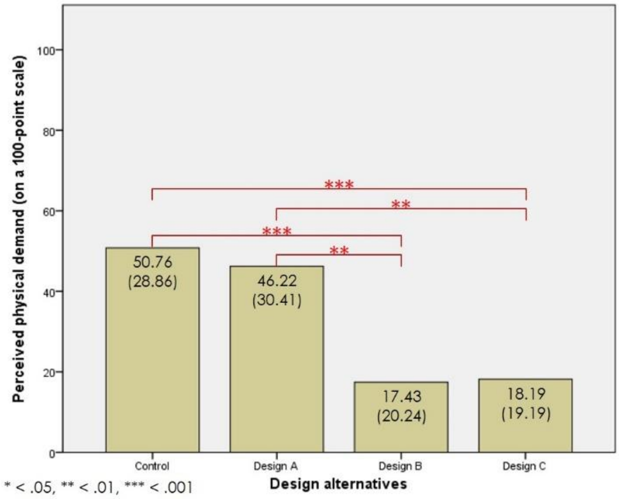

Figure 4.11: Bar graph for perceived physical demand with mean (standard deviation) values and asterisks indicating significance in the pairwise comparisons

4.3.2 Discussion

The study results provided empirical evidence that well-designed CMSs could indeed significantly reduce physical demands of driving. All three CMS display layouts examined in this study provided advantages over Control albeit they differed in the types and magnitudes of the advantages (Figures 4.9, 4.10 and 4.11). Compared to Control, Design A showed 20.4% reduction in the mean spread of eye gaze positions; Design B showed 55.8% reduction in the mean spread of eye gaze positions, 62.0% reduction in the mean spread of head position, and 65.7% reduction in the mean perceived physical demand. Design C showed 48.0%, 59.7% and 64.2% mean reductions, respectively.

It should be pointed out that the study results presented in Figures 4.9, 4.10 and 4.11 could be also explained largely by the inter-distances between the major gaze points – again, the positions of the normal line-of-sight when looking straight ahead and the two side-view displays represent the major gaze points during the experiment task. Since gaze transition is achieved through the combination/coordination of eye and head movements (Kim, Reed and Martin 2010; Normark and Gärling 2011), increased inter-distances between the gaze points would logically incur increases in some or all of the three physical demand measures considered in the current study. Figures 4.9, 4.10 and 4.11 present observations largely consistent with this expectation. From Control to Design A to Design B to Design C, the sum of the inter-distances between the gaze points decreases, and, such decrease resulted in reductions in physical demand measures. From Control to Design A, only the spread of eye gaze positions significantly decreased, as mentioned earlier. Compared with Control and Design A, Designs B and C exhibited significant reductions in all three physical demand measures. Thus, one design characteristic leading to reduced physical demands could be specified as small inter-distances between the major gaze points. Since the driver must look at the road ahead most of the time during driving, this design characteristic could be phrased as 'side-view displays located close to the position of the normal line-of-sight when looking at the road ahead.' Especially, the current study results indicate that placing the two side-view displays close to/within the driver's central field of view as in Designs B and C, can significantly reduce the overall physical demands. Relatedly, some human factors design guidelines/standards suggested that critical or frequently used automotive displays should be located close to/within the central visual field (within about 15 to 30 degrees from the normal line-of-sight), so as to be checked with quick eye movements and minimal head movements and neck strain (Green et al. 1994; Ahlstrom and Kudrick 2007; Bhise 2011).

While the inter-distances between the gaze points could be utilized as a basis for interpreting most of the observations presented in Figures 4.9, 4.10 and 4.11, it does not help account for one observation – the mean spread of eye gaze positions being larger for Design C than Design B (Figure 4.9). This observation is opposite to the prediction based on the inter-distances between the gaze points as the sum of the inter-distances was smaller for Design C than Design B. Logically, this would be possible only if the participants viewed the side-view displays more frequently for Design C than Design B during the experiment trials.

In order to confirm this possibility, post-hoc analyses of the participants' gaze behavior were performed as follows. An in-depth examination of the eye tracking video clips revealed that in performing the task trials, the participants' gaze pattern generally took the triangular form with vertices at the three gaze points – the normal line-of-sight to one of the two side-view displays to the other side-view display to the normal line-of-sight (Figure 4.12). In other words, the participants mostly viewed the side-view displays twice, once for each side in a sequential manner. However, the participants occasionally conducted task trials with less than two glances (i.e., with a single glance or no glance at all) or with more than two glances. Task trials with more than two glances involved back-and-forth gaze shifts between the two side-view displays.

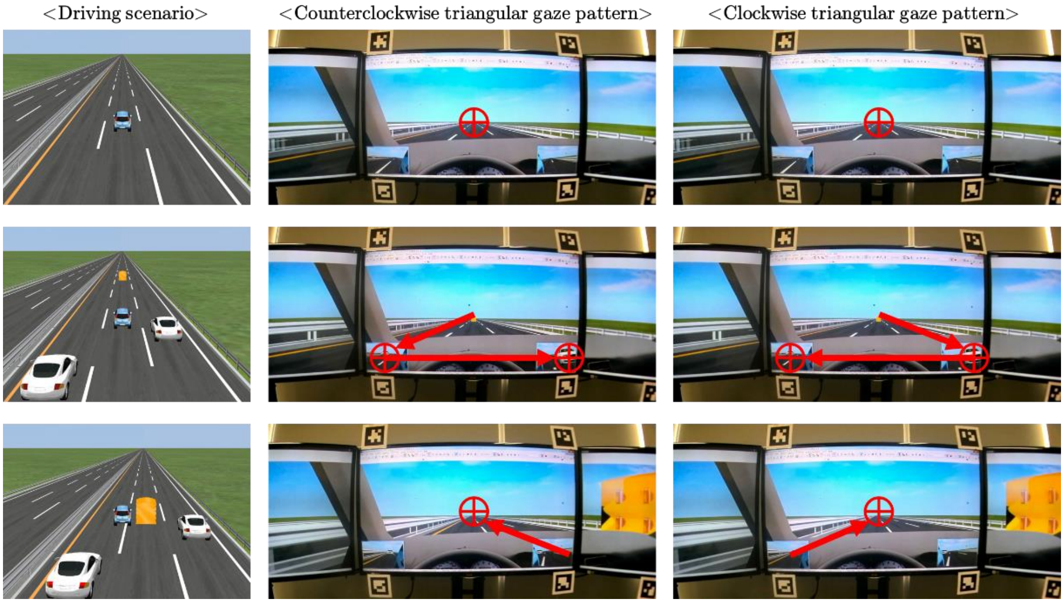

Figure 4.12: The participants' general gaze patterns in performing the task trials

For each task trial, the number of glances to the side-view displays was counted and a frequency analysis was conducted. The definition of a glance was based on International Standard ISO 15007-1:2014. Figures 4.13(a) and 4.13(b) show the frequencies of trials conducted with less than two glances and more than two glances, respectively, for each display layout. Subsequently, one-way repeated measures ANOVA and post-hoc Bonferroni multiple comparisons were conducted to compare the number of glances to the side-view displays for the four layout design alternatives – since each participant performed the task trial five times for each design alternative, the mean of the five data points was used for the statistical tests. The layout design significantly affected the number of glances with a p-value less than 0.05. Figure 4.13(c) shows the results of the post-hoc Bonferroni multiple comparisons on the number of glances to the side-view displays for each design.

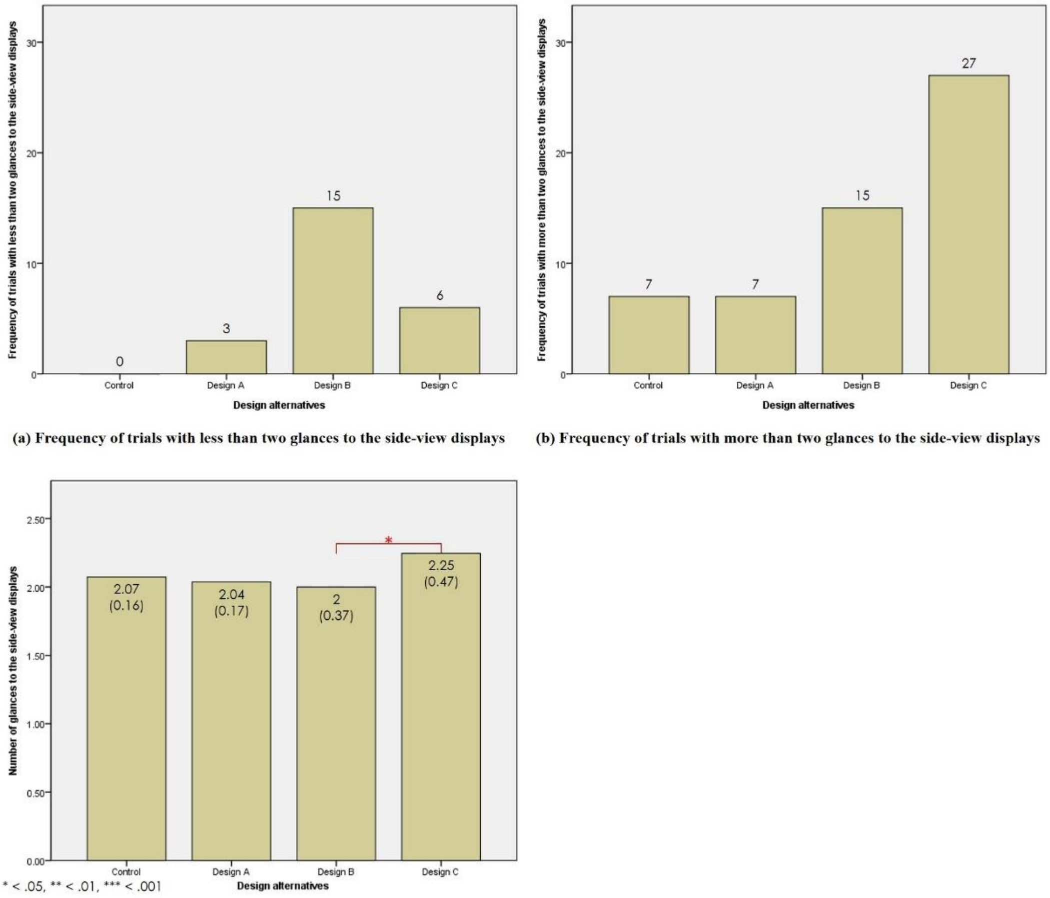

Figure 4.13: Bar graphs for (a) frequency of trials with less than two glances to the side-view displays, (b) frequency of trials with more than two glances to the side-view displays, and (c) number of glances to the side-view displays with mean (standard deviation) values and asterisk indicating significance in the pairwise comparisons

Three observations could be made from the post-hoc analyses: 1) the frequency of less than two glances was highest for Design B (Figure 4.13(a)), 2) the frequency of more than two glances increased as it went from Control/Design A to Design B to Design C (Figure 4.13(b)), and 3) the mean number of glances to the side-view displays was statistically significantly larger for Design C than Design B (Figure 4.13(c)).

The observation of Design B having the highest frequency of less than two glances (Figure 4.13(a)) suggests that the two side-view displays in close proximity to each other allowed the visual information to be processed simultaneously within a single glance. Also, the two displays might have served as a configural display, thus requiring a single glance for decision making – again, such display is known to combine different information pieces into an integrated object, and facilitate pattern perception by providing a useful emergent feature (Sanders and McCormick 1993; Wickens et al. 2004). Relatedly, International Standard ISO 9355-1:1999 also stated that in a human-machine system, displays that are close together may be perceived as a unit, allowing more efficient information processing.

The gradual increase in the frequency of more than two glances from Control/Design A to Design B to Design C (Figure 4.13(b)) may be because the layout design became less compatible with the driver's previous experience/expectation, and thus, became more likely to confuse the driver and cause back-and-forth gaze shifts between the two displays. Especially, again, Design C violates compatible spatial relationship with the left side-view display on the right side with respect to the driver's egocentric axis (Umiltà and Liotti 1987; Esser 2016). This non-compatible design element in Design C could explain 1) why Design C showed lower frequency of less than two glances than Design B, although better satisfying the above condition for simultaneous information processing (i.e., close proximity of the two displays to each other), and 2) why Design C showed an exceptionally high (the highest among all designs) frequency of more than two glances. Large et al. (2016) reported a comparable result that among the five different CMS display layout designs examined in the study, only the one similar to Design C showed significantly more frequent gaze shifts between the left and right side-view displays – the authors also attributed this to the confusion resulting from the right side-view display being located to the left of the driver.

The statistically significant difference between Designs B and C in the average number of the glances to the displays (Figure 4.13(c)) resulted from the large number of trials with more than two glances found for Design C (Figure 4.13(b)). Collectively, the three observations from the post-hoc analyses of the participants' gaze behavior seem to account for the finding that Design C showed larger spread of eye gaze positions than Design B, despite the smaller inter-distances between the gaze points. Also, these observations empirically confirmed the two possible explanations suggested above in Chapter 4.2.2 for the reasons Design C did not show the best results despite the smallest combined inter-distance – the explanations were: 1) the inter-distance between the two displays in Design B was small enough to enable simultaneous information processing, and 2) the non-compatible design element of Design C adversely affected information processing.

It may be worth noting that the results of the statistical analyses for the perceived physical demand ratings (Figure 4.11) were identical to those for the spread of head positions (Figure 4.10) in the overall pattern, but were not so to those for the spread of eye gaze positions (Figure 4.9). These findings seem to suggest that the biomechanical stresses imposed on the head-neck muscles had stronger influences than those on the ocular muscles on the participants' subjective assessment of the physical demands. Compared with the eye motor system consisting of visco-elastic plants (the eyes) and six extraocular muscles, the head motor system is more complex and requires more physical resources - the head is a visco-inertial plant much heavier than the eyes and its movement requires coordination of more than twenty muscles (Corneil 2011). Relatedly, Kim, Reed, and Martin (2010) have stated that while both eye and head movements normally constitute the angular distance to a visual target, the magnitude of head movements should be separately considered due to its direct relationship to musculoskeletal symptoms and discomfort.

Overall, the current study demonstrated that a well-designed CMS side-view display layout could reduce the physical demands associated with checking side and rear views. One design characteristic leading to reduced physical demands was small inter-distances between the three gaze points. In particular, locating the side-view displays close to/within the central visual field (close to the normal line-of-sight when looking at the road ahead) could significantly reduce the overall physical demands (driver's eye movements, head movements and subjective assessment of the physical demands). However, it was found that sacrificing too much compatibility for reducing the inter-distances between the gaze points could adversely affect the information processing, leading to driver's confusion and additional back-and-forth gaze shifts between the side-view displays. Thus, maintaining compatibility could be another design characteristic for reduced physical demands.

The findings of the current study seem to suggest that good interface design that enhances human information processing by reducing information access costs and maintaining compatibility could result in reduced physical stresses, in addition to improving user task performance. In fact, such impacts of good interface design on physical stresses have been demonstrated in several previous studies (Karwowski et al. 1994; Lehman and Marras 1994; Lee et al. 2007; Hu and Ning 2016).

While beneficial to all drivers, physical demand reduction by CMS displays would especially benefit drivers frequently checking the side-view mirrors with large eye/head movements and physically weak or impaired drivers. Such drivers include:

- Drivers of large-sized commercial vehicles (e.g., buses, vans, trucks) who need to check the side-view mirrors 1) with large eye and head movements due to the vehicle's large inter-distance between the two mirrors, and 2) frequently for picking up and dropping off people/goods or monitoring the goods or surroundings (ISO 16505:2015; Blomdahl 2016). Schmidt et al. (2016) also considered the reduced head movements from CMS displays especially beneficial for truck drivers.
- Drivers who tend to sit or lean more forward (e.g., short drivers), and thus, need to check the side-view mirrors with larger eye and head movements

(Devlin 1968; Parkin, Mackay and Cooper 1995; McFadden et al. 2000; Park et al. 2000; Bhise 2011).

- Drivers with reduced body mobility or physical discomfort/illness (e.g., older drivers or arthritis patients) who would experience physical demands more easily while checking side-view mirrors (Alliance of Automobile Manufacturers and Tesla Motors, Inc. 2014; Large et al. 2016; Terzis 2016).

4.4 Concluding Remarks and Future Research Directions

The study results demonstrated that well-designed CMS side-view display layouts could significantly enhance driving performance, safety, and comfort. Compared to the traditional mirror system, all of the three CMS side-view display layouts examined in this study resulted in improved driver information processing and reduced physical demands of driving, albeit they differed in the types and magnitudes of the advantages. Design characteristics that led to such beneficial effects include placing CMS displays close to the position of the normal line-of-sight when looking at the road ahead and locating each CMS display on each side of the driver, that is, at locations compatible with the driver's expectation. This is consistent with the automotive ergonomics design guideline that in-vehicle displays should be placed in locations that involve minimal head/torso movements and, also those that can be expected so as to be quickly checked with minimal mental and physical efforts (Bhise 2011).

Some words of caution may be in order here in regard to the use of the study findings: first, in the current study, the participants conducted a task that demanded rapidly acquiring and integrating visual information from multiple sources and making a critical decision to avoid an imminent danger. The study findings can be reasonably extended to make predictions about similar tasks. However, they may not be generalized to tasks of different nature. For example, Design B may not turn out to be the best design in ordinary, non-safety-critical lane change tasks - indeed, in the previous studies by Large et al. (2016) and Schmidt et al. (2016), which examined non-safety-critical lane change tasks, a design alternative similar to Design A of the current study, not Design B, was found to be the most preferred one. Thus, design alternatives must be evaluated for the full range of plausible or important driving tasks and also in different driving situations to fully understand their differences; then, the evaluation results must be taken together to make informed design decisions.

Second, it should be noted that in comparatively evaluating the three CMS side-view display layouts, this study did not consider their impacts on other in-vehicle display/control elements and related tasks. Locating the CMS displays within the dashboard area, as in Designs B and C, will result in moving some of the conventional elements that would normally occupy the area to somewhere else. This would affect overall driver behavior and experience in human-vehicle interactions. Another potential challenge in placing the CMS displays close to the driver is that brightness and motion of the displayed images may cause disturbance/distraction (Fornell Fagerström and Gårdlund 2012). Placing moving, light-emitting visual stimulus close to eyes can also lead to visual discomfort or fatigue, especially in low light conditions (e.g., at night). Thus, the problem of spatially arranging side-view displays should be understood as part of the larger in-vehicle display system design problem.

Third, the current study is a simulator study. According to Mullen et al. (2011) who had reviewed many previous driving simulator studies, driving behavior in simulators does not exactly replicate (absolute validity) but approximate (relative validity) on-road driving behavior with medium to strong correlations, and this is sufficient for the majority of research, training, and assessment purposes. In light of this, the current simulator study seems to adequately serve its purpose – that is, a comparative evaluation of design alternatives. However, as pointed out by Mullen et al. (2011), on-road measures will need to be employed for future research efforts seeking absolute validity.

Finally, several future research directions are provided here:

First, as mentioned above, side-view display layout design alternatives need to be evaluated considering different driving tasks and situations to properly inform design decisions. Some research questions in line with this are as follows:

- Does the effect of side-view display layout design change across different driving speeds? Especially, what is the impact of high-speed driving? Related to this question, Sanders and McCormick (1993) reported that increasing speed is accompanied by a narrowing of visual scanning area.
- Is the effect of side-view display layout design modified by environmental conditions? What are the impacts of the night-time, bad weather, curved road and/or high traffic density conditions? According to a study by Senders et al. (1967), the average amount of time the subjects were willing to keep their eyes closed (i.e., the eyes-off-the-road time) was reduced in demanding road environment such as curves at night compared to empty road in daylight.
- Does the effect of side-view display layout design change across different driver workload levels? Some studies showed that increased levels of information processing load resulted in a narrowing of the functional field of view (Mackworth 1965; Lee and Triggs 1976; Williams 1985).

- Does the effect of side-view display layout design differ between novices and experienced drivers? Relatedly, Mourant and Rockwell (1972) reported that novice drivers sample the roadway environment more narrowly than experienced drivers.
- Does the effect of side-view display layout design differ between male and female drivers? Relatedly, Hada (1994) reported that female drivers looked at in-vehicle displays slightly more frequently and longer than male drivers while driving.
- Does the effect of side-view display layout design differ between younger and older drivers? Terzis (2016) stated that the eye accommodation ability decreases with age and this must be taken into consideration when introducing CMS and determining the position of the displays. Also, aging is associated with changes in human abilities such as a slowing of performance, decline in working memory capacity, difficulty in dealing with incompatibility, decrease in size of lateral visual field, and reduction in body mobility (Sanders and McCormick 1993; Wickens et al. 2004, 2013; Bhise 2011).
- How does the effect of side-view display layout design differ in driving situations where the driving task is performed by an automated driving system? Does the design effect change across different levels of automation

– namely, conditional (level 3), high (level 4) and full (level 5) automation (SAE J3016 2014)? Especially, what are the design characteristics of CMS display layouts that can help the human driver respond appropriately to a request to intervene and resume the driving task?

Second, training is considered important for driver acceptance of and adaptation to the CMS technology (Mohamed Ali and Fatin Bazilah 2014; Large et al. 2016; Schmidt et al. 2016). Training will improve performance on both compatible and incompatible mappings, and the improvement rate may be faster with incompatible ones because they have more room for improvements (Wickens et al. 2013). In this sense, training might facilitate the driver's adaptation of the mental model and driving behavior especially to CMS display layouts with compatibility issue (Design C in this study). However, practicing with incompatible interface may not improve performance to the level acquired by practicing with a more compatible one – moreover, under stress conditions (as in this study), performance will regress further with less compatible interface, or operators can revert to existing stereotypes even if trained to act in a contrary manner (ISO 9355-1:1999; Wickens et al. 2013; Proctor and Vu 2016). Hence, it would be worth investigating how training affects the current study results.

Third, while contributing to physical demand reduction, head movement reduction by CMS displays may not be always desirable as it could have negative effects on drivers' situation awareness of the surroundings, and thereby, safety. For example, drivers with reduced head movement may not see what is visible only with large head movements, such as over-the-shoulder checks/glances for checking blind spots. However, with potential benefits such as visual field expansion and blind spot elimination, CMS displays can rather enhance driving safety by allowing drivers to keep focused on the road ahead without having to do the head movements or shoulder checks required in the traditional mirror systems. These safety-related trade-offs would need to be carefully investigated through future research efforts.

Lastly, the current study did not examine true emergency behaviors of drivers as the participants experienced the lane changing situation many times (five times for each of the four design alternatives). A follow-up study employing unexpected critical event scenarios will further enhance our understanding of the impacts of different side-view display layout designs. Related to empirical examination of drivers' true emergency behaviors, Caird and Horrey (2011) suggested using different types of scenarios and event configurations to prevent participants' anticipation of particular events, and Kearney and Grechkin (2011) suggested providing secondary tasks to divert their attention.

Chapter 5

Conclusion

5.1 Summary and Implications

5.1.1 The Survey Study on HUD Information Items

This study identified six high-importance information items. They are: current speed, speed limit, turn-by-turn navigation instructions, maintenance warning, cruise control status and low fuel warning. These information items may serve as the default information items for automotive HUD systems. Additional optional items could be determined based on an individual driver's information preference and needs, and, may be presented to the driver adaptively according to the driving context at hand.

The six high-importance HUD information items identified in this study exhibit some common characteristics: demanding frequent or continuous attention, requiring fast perception and reaction, necessitating correct information processing, and/or being unobtainable from the outside road view. These characteristics may be utilized as general criteria for predicting a certain information item's perceived importance level and further making design decisions on whether to introduce new information items into a HUD system.

The current study demonstrated that survey participants need actual information item experience in order to adequately evaluate the importance of HUD information items. Thus, future research efforts for evaluating information items' importance must involve data collection from drivers with not only HUD use experience but also relevant information item experience. For novel information items for which drivers with prior information item experience cannot be found, it may be useful to provide some simulated information item experience to the study participants using a realistic driving simulator prior to data collection - further empirical studies are needed to confirm the efficacy of such simulated information item experience approaches

Also, this study reported the results of a user survey on the usage contexts and design improvement points of the existing automotive HUD systems for eleven high-priority HUD information items (current speed, speed limit, turn-by-turn navigation, maintenance warning, cruise control status, audio player status, traffic sign, distance to destination, gear position, RPM and low fuel warning). The survey results provided some useful insights on user experience and use practices of automotive HUD users. Future research directions were also identified on the basis of the survey results.

The study findings are expected to greatly benefit the design of future automotive HUD systems which could adequately present only the necessary and important information according to the driving situation at hand. For example, it is possible to suggest the eleven high-priority HUD information items be presented in the following driving contexts:

- Current speed – always while driving, considering its highest priority and the drivers' frequent misjudgment of the vehicle speed.
- Speed limit and cruise control – when speed control becomes especially important as in the enforcement sections or on the highways.
- Gear position and RPM – when engine/transmission control requires driver attention as in manual shift mode, and sporty or economical driving.
- Turn-by-turn navigation, traffic sign and distance to destination – when wayfinding, especially in complex roads or new/unfamiliar places.

- Maintenance warning and low fuel warning – when the warning requires fast detection and reaction from the driver.
- Speed limit and traffic sign – when rapid detection of the road sign becomes essential for correct and safe maneuvers as in areas with potential hazards (e.g., sharp curve) or poor visibility.
- Audio player status – when manipulating currently playing audio tracks or radio stations while driving.

These design suggestions could serve as the default settings of the conditions for turning on/off certain HUD information items. Based on these settings, providing user-customizable features allowing users to decide what to display and specify the display-on/off conditions could address the individual- and context-specific HUD information needs.

5.1.2 The Driving Simulator Study on CMS Display Layouts

Overall, the current study demonstrated that well-designed CMS side-view display systems could outperform the conventional side-view mirror system in assisting the driver in performing a safety-critical task (making a lane change to avoid future collisions). Among the three side-view display layouts examined in this study, Designs A and B consistently surpassed Control, and Design B was superior to Design A across all of the information processing measures. Also, Designs B and C showed reductions in all three physical demand measures, and Design B exhibited less spread of eye gaze positions than Design C. Thus, in the particular context of the experiment task considered in this study, Design B can be recommended as the best design, both in terms of driver information processing and physical demands of driving. Table 5.1 provides a summary of the results. The results were fairly consistent across all of the eight dependent measures considered in this study. This suggests that the measures were correlated with one another, which was confirmed by the correlation matrix (Figure 5.1).

Table 5.1: Summary of the results of the study on CMS display layouts

	Measures	Designs with statistically significant differences in pairwise comparisons Inferior ←——————————→ Superior
Information processing	Eye-off-the-road time	Control > Design A > Designs B & C
	Response time	Control > Design A > Designs B & C
	Perceived workload	Control > Designs A & C > Design B
	Preference	Control < Design A < Design B Design C < Design B
	Perceived safety	Control < Design A < Design B Design C < Design B
Physical demands	Spread of eye gaze positions	Control > Design A > Design C > Design B
	Spread of head positions	Control & Design A > Designs B & C
	Perceived physical demand	Control & Design A > Designs B & C
	Number of glances to the side-view displays	Design C > Design B

*Note: 'X > Y' indicates that X is significantly larger than Y.

*Note: 'X & Y' indicates that there is no significant difference between X and Y.

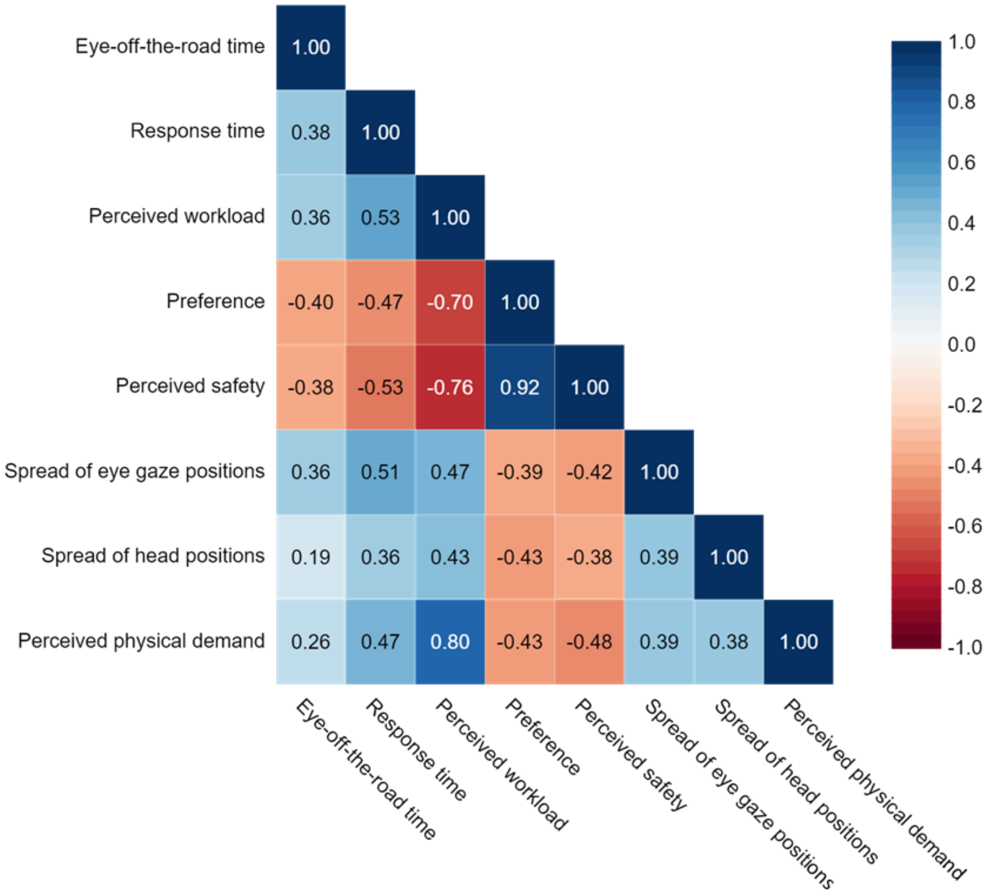

Figure 5.1: Matrix of Pearson's correlation coefficients for all of the eight dependent measures considered in the study on CMS display layout (every correlation was statistically significant, with each p-value less than 0.05)

Also, the current study demonstrated the importance of the basic ergonomics design principles in the design of CMS side-view display systems. In particular, this study showed that, in determining the display layout, it is important to reduce the eye gaze travel distance (inter-distances between the three major gaze points) and maintain compatible spatial relationships - this is consistent with the notion in the automotive ergonomics literature that automotive displays should be located based on eye movement and driver expectancy so as to be found with a minimum search-and-recognition time (Bhise 2011). The two design characteristics, reducing eye gaze travel distance and maintaining compatible relationships, may conflict with each other in making certain design situations. As demonstrated in this study, sacrificing one objective excessively for accomplishing the other can reduce the benefits of the CMS side-view displays system, and, thus, the trade-offs must be carefully studied to optimize the design.

5.2 Future Research Ideas

As an effort to contribute to the ergonomics design of automotive HUD system and CMS, this dissertation was focused on 1) the HUD information items' importance, usage contexts and design improvement points, and 2) the effects of CMS side-view display layout design on the information processing and the physical demands. More ergonomics research for these non-traditional in-vehicle display systems will be necessary in the future. Some future research ideas are provided here:

5.2.1 HUD system

The current study was focused on commercially available information items displayed by the existing HUD systems, without considering contact-analog information items provided by augmented reality (AR) HUD systems – by overlaying and moving with outside elements, they are known to help reduce divided attention and cognitive load from matching the augmented images with the real world (Gish and Staplin 1995; Narzt et al. 2006; Kim and Dey 2009; Plavšic et al. 2009). Some studies have developed novel HUD concepts providing contact-analog navigation and demonstrated their potential benefits in terms of driver attention, workload, and driving/navigating performance (Poitschke et al. 2008; Kim and Dey 2009; Medenica et al. 2011; Bark et al. 2014; Yoon et al. 2014; Pfannmüller et al. 2015). Despite the benefits, however, there are some ergonomics issues to be addressed for their successful implementation/commercialization, such as visual interference/clutter, and driver distraction/annoyance (Bark et al. 2014; Gabbard, Fitch and Kim 2014; Pfannmüller et al. 2015). For example, since a great amount of contact-analog information could amplify the risk of obscuration, future studies are needed to determine 1) the extent to which such augmented images are applied and 2) the situations where 2D-unregistered symbol suffices (Plavšic et al. 2009).

5.2.2 CMS

Future studies may explore additional design ideas for further improving the best design in this study, Design B. One possible design idea would be to place the two side-view displays closer to the driver (the egocentric axis) within the instrument panel, which would further reduce the eye gaze travel distance while maintaining the compatible spatial relationships. In this case, however, a series of information items provided through the instrument panel (e.g., current speed, gear position, RPM, fuel level) would have to be presented somewhere else, which could affect the overall driving performance and driver experience. Another possible design idea for improving Design B would be to provide blind spot/object detection warnings through CMS displays with conspicuous effects (e.g., flashing, enlarging) so that the driver can immediately perceive the safe direction for lane change through peripheral vision, without having to check both side-view displays. However, such visual effects should be carefully applied not to compel too much attention or annoy the drivers. Further empirical studies will be needed to examine if these design ideas can indeed contribute to enhancing the ergonomics design of CMS.

Also, the current study was focused on the layout of CMS displays, and, therefore, simplifying assumption was made regarding the provided field of view. As mentioned earlier, CMS displays can expand the visual field through wide-angle camera lenses. Also, CMS displays can adaptively alter the provided field of view in response to certain triggers (e.g., the use of reverse gear) through image processing – it can simulate head movements by cropping and moving the view (Fornell Fagerström and Gårdlund 2012). Such expanded/altered view can not only enhance situation awareness, but also reduce the head/body movements that have been previously required in the mirror system for changing/panning of what is seen in the mirrors, especially in reversing, turning, or driving in roundabouts, etc. (ISO 16505:2015). However, the expanded view may cause size and distance misperception of the objects behind/beside the vehicle – they would look smaller in the displays and thus be judged farther away than they really are. Also, the expanded/adjusted view can increase the amount of information shown in the displays, causing information overload or visual clutter. According to Hick-Hyman law (Hick 1952; Hyman 1953), increased amount of transmitted information is associated with increased reaction time. Further studies are needed to understand how these functions affect physical and cognitive demands of driving.

In addition, future studies may explore new CMS display designs, including CMS rear-view display. For example, the three CMS displays (left side-view display, rear-view display, and right side-view display) may be integrated into one display, allowing driver to comprehensively check side and rear views with a single glance while driving. Relatedly, proximity compatibility principle states that tasks requiring high task or mental proximity will benefit from high display proximity (Wickens et al. 2004, 2013). However, the integrated display can hardly maintain the above compatible relationships with respect to the egocentric axis (unless horizontally located in front of the driver), or also may cause information overload by providing multiple views at once. Moreover, if the three views (left side view, rear view, and right side view) are simply joined side-by-side but remain separated within the display, certain objects will be displayed redundantly in two or three views, causing driver confusion. Through image processing, the three views can be stitched into a coherent/continuous view with a representation of his/her own vehicle at the bottom center of the display – thus, making the image seem to come from a single rear-facing camera in front of the vehicle, allowing driver's natural/intuitive situation awareness. However, this stitched view may cause driver confusion over the left-right orientation due to image reversal of the familiar front view of his/her own car – driver is generally accustomed to seeing the front view of his/her own vehicle 'directly outside the vehicle', not 'indirectly (as a mirror image) inside the vehicle'.

5.2.3 HUD system and CMS

Lastly, the two non-traditional in-vehicle displays reducing information access costs, automotive HUDs and CMS displays, could be designed to be used effectively in combination to further enhance driving performance, safety, and comfort. For example, the driver confusion resulting from CMS display layout designs with less or non-compatible spatial relationship could be reduced by providing blind spot/object detection warning with left-right directional information on HUD, as in some OEM HUD systems (e.g., Genesis, Hyundai, KIA). Also, certain important information items can be provided through both HUD and CMS displays, based on the principle of redundancy that important information should be available from different sources to benefit overall system safety/efficiency. Presenting identical information redundantly on multiple displays may improve its noticeability, but at the same time, annoy or distract drivers. Thus, future studies are needed to examine these design possibilities and to determine which information items should be presented singly or redundantly on which in-vehicle display(s) (among HUD, left side-view display, right side-view display, and even rear-view display).

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Appendix A. The t-test tables

Table A.1: The results of the t-tests conducted to examine the impact of user's prior information item experience on the evaluation of the item's importance

Information	Importance rating scores of participants with prior `information item' experience			Importance rating scores of participants without prior `information item' experience		
	N	Mean	SD	N	Mean	SD
Speed limit	36	4.64	.59	15	4.47	.74
Maintenance warning	26	4.69	.62	25	3.24	1.27
Cruise control status	32	4.38	.71	19	2.84	1.30
Audio player status	29	3.90	.90	22	2.86	1.46
Traffic sign	17	3.65	.93	34	3.21	1.23
Distance to destination	17	3.47	1.13	34	3.15	1.11
Gear position	18	3.50	.99	33	3.09	1.28
Low fuel warning	26	4.12	.99	25	1.88	1.01

Information	Levene's Test for Equality of Variances		t-test for Equality of Means		
	F	Sig.	t	Sig.	Mean difference
Speed limit	2.055	.158	.876	.385	.172
Maintenance warning	12.319	.001	5.169	.000	1.452
Cruise control status	6.887	.012	4.733	.000	1.533
Audio player status	10.135	.003	2.928	.006	1.033
Traffic sign	2.511	.120	1.305	.198	.441
Distance to destination	.464	.499	.980	.332	.324
Gear position	1.902	.174	1.175	.246	.409
Low fuel warning	.065	.799	7.957	.000	2.235

Appendix B. The ANOVA tables

Table B.1: The ANOVA results for eye-off-the-road time

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.662	8.132	5	.150	.786	.989

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	3.864	3	1.288	22.111	.000
	Greenhouse-Geisser	3.864	2.358	1.639	22.111	.000
	Huynh-Feldt	3.864	2.675	1.445	22.111	.000

Table B.2: The ANOVA results for response time

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.695	7.172	5	.209	.838	.961

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	1.600	3	.533	37.304	.000
	Greenhouse-Geisser	1.600	2.513	.637	37.304	.000
	Huynh-Feldt	1.600	2.882	.555	37.304	.000

Table B.3: The ANOVA results for perceived workload

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.207	31.061	5	.000	.502	.533

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	22638.761	3	7546.254	26.460	.000
	Greenhouse-Geisser	22638.761	1.506	15027.633	26.460	.000
	Huynh-Feldt	22638.761	1.598	14170.661	26.460	.000

Table B.4: The ANOVA results for preference

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.289	24.450	5	.000	.582	.630

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	221.943	3	73.981	24.556	.000
	Greenhouse-Geisser	221.943	1.745	127.210	24.556	.000
	Huynh-Feldt	221.943	1.890	117.460	24.556	.000

Table B.5: The ANOVA results for perceived safety

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.299	23.838	5	.000	.583	.632

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	185.852	3	61.951	24.796	.000
	Greenhouse-Geisser	185.852	1.750	106.213	24.796	.000
	Huynh-Feldt	185.852	1.896	98.030	24.796	.000

Table B.6: The ANOVA results for spread of eye gaze positions

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.093	46.930	5	.000	.444	.462

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	377.450	3	125.817	50.460	.000
	Greenhouse-Geisser	377.450	1.331	283.612	50.460	.000
	Huynh-Feldt	377.450	1.387	272.154	50.460	.000

Table B.7: The ANOVA results for spread of head positions

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.404	17.876	5	.003	.621	.679

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	14.303	3	4.768	27.343	.000
	Greenhouse-Geisser	14.303	1.864	7.673	27.343	.000
	Huynh-Feldt	14.303	2.038	7.017	27.343	.000

Table B.8: The ANOVA results for perceived physical demand

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.272	25.652	5	.000	.561	.604

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	20948.994	3	6982.998	21.011	.000
	Greenhouse-Geisser	20948.994	1.682	12452.493	21.011	.000
	Huynh-Feldt	20948.994	1.812	11558.863	21.011	.000

Table B.9: The ANOVA results for number of glances to the side-view displays

Mauchly's Test of Sphericity						
Within Subjects Effect	Mauchly's W	Approx. Chi-square	df	Sig.	Epsilon	
					Greenhouse-Geisser	Huynh-Feldt
Design	.409	17.651	5	.003	.664	.733

Tests of Within-Subjects Effects						
Source		Type Ⅲ Sum of Squares	df	Mean Square	F	Sig.
Design	Sphericity Assumed	.780	3	.260	3.432	.022
	Greenhouse-Geisser	.780	1.991	.391	3.432	.042
	Huynh-Feldt	.780	2.200	.354	3.432	.037

국문초록

운전자가 차량을 온전히 제어하면서 도로 상황을 인지하기 위해서는 주행 중 대부분의 시간 동안 전방을 주시해야 한다. 따라서, 일련의 주행 업무에 필요한 정보를 제공하는 차량 내 디스플레이를 운전자의 전방 시선에 가깝게 위치시켜서 운전자의 시선이 전방을 벗어난 시간을 감소시키는 것이 중요하다. 자동차 헤드-업 디스플레이(Head-Up Display, 이하 HUD) 시스템과 카메라 모니터 시스템(Camera Monitor System, 이하 CMS)은 정보 접근 비용을 감소시켜줄 수 있는 유망한 비전통적 차량 내 디스플레이 시스템이다. HUD는 다양한 정보를 운전자의 전방 시야 상에 직접 제공하여, 운전자로 하여금 기존의 대시보드 영역에 위치했던 디스플레이(헤드-다운 디스플레이)를 향해 시선을 내리지 않고도, 전방을 주시하면서 필요한 정보를 얻을 수 있게 해준다. CMS는 차량의 후측방 시야를 카메라로 포착하여, 실시간으로 차량 내 디스플레이로 보여주어, 운전자로 하여금 후측방 정보를 기존의 외부 사이드-뷰 미러를 향해 시선을 돌리지 않고도, 차량 내부에서 얻을 수 있게 해준다.

HUD 시스템과 CMS의 잠재적인 이점 및 유망한 응용 방안에도 불구하고, 이러한 비전통적 차량 내 디스플레이 시스템의 인간공학적 설계를 위해서 해결해야 할 몇가지 중요한 연구 문제들이 있다. HUD 시스템의 경우, 많은 정보 요소들을 무분별하게 제공할 경우, 정보 과다(Information overload), 시각적 혼잡(Visual clutter), 인지 포획(Cognitive capture)과 같은 부정적인 결과를 초래할

수 있다. 따라서, 오직 필요하고 중요한 정보만 선별하여 주행 상황에 따라 적절히 제공해야 할 것이다. CMS의 경우, CMS 디스플레이가 기존의 사이드-뷰 미러 위치 대신, 차량 내 임의의 위치에 놓일 수 있는데, 이러한 디스플레이 배치 설계의 유연성은 운전자의 정보 처리를 용이하게 하고, 후측방 상황 파악에 수반되는 신체적 부하를 경감시키는데 활용될 수 있다.

따라서, 본 논문에서는 다음의 인간공학 연구 문제들을 고려하였다: 1) '현재 HUD 시스템에서 표시되는 다양한 정보 요소들 중에, 어떤 것들이 중요한가?', 2) '중요한 HUD 정보 요소들은 주행 상황에 따라 어떻게 제공되어야 하는가?', 3) '운전자의 정보 처리를 용이하게 해줄 수 있는 CMS 디스플레이 배치의 설계 특성은 무엇인가?', 4) '주행의 신체적 부담을 감소시켜줄 수 있는 CMS 디스플레이 배치의 설계 특성은 무엇인가?' 이러한 연구 문제들과 관련된 몇가지 중요한 지식의 격차를 해소하고 이러한 비전통적 차량 내 디스플레이 시스템의 인간공학적 설계에 기여하기 위한 노력의 일환으로, HUD 정보 요소에 대한 연구와 CMS 디스플레이 배치에 대한 연구가 수행되었다.

HUD 정보 요소에 대한 연구에서는, 사용자 설문 조사를 수행하여, 1) 현재 상용화된 HUD 시스템에서 표시되는 22가지 정보 요소들에 대해 사용자가 인지하는 중요도를 결정하고 2) 우선 순위가 높은 HUD 정보 요소들에 대해 사용 상황 및 사용자가 인지하는 설계 개선점을 검토하였다. HUD를 사용해 본 경험이 충분히 많은 51명의 운전자들이 설문에 참가하였다. 각 정보 요소에 대해서 피설문자들은 그 정보의 중요도를 주관적으로 평가하고, 해당 정보의 사용 상황 및 설계 개선점을 기술하였다. 설문 결과, 정보 요소들 마다 중요도가 크게

달랐으며, 현재 속도, 제한 속도, 턴-바이-턴 네비게이션 안내, 차량 정비 경고, 크루즈 컨트롤 상태, 연료 부족 경고가 가장 높은 중요도를 보였다. 11가지 높은 우선순위의 HUD 정보 요소들에 대해서는, 설문 응답들을 토대로, HUD 시스템의 인간공학적 설계를 위한 설계 시사점 및 추후 연구 방향들이 도출되었다.

CMS 디스플레이 배치에 대한 연구에서는, 주행 시뮬레이터 실험을 수행하여, 세 가지 각기 다른 CMS 디스플레이 배치들과 기존의 사이드-뷰 미러 배치를 1) 운전자의 정보 처리 및 2) 주행의 신체적 부담의 측면에서 비교 평가하였다. 세 가지 디스플레이 배치에서는 좌우 CMS 사이드-뷰 디스플레이가 각각 기존 사이드-뷰 미러 바로 안쪽에, 스티어링휠의 양쪽 대시보드 상에, 나란히 붙여서 센터페시아 상에 위치하였다. 22명의 피실험자가 각 배치 대안으로 위험한 차선 변경 태스크를 수행하였다. 기존 미러 시스템에 비해, 세 가지 CMS 디스플레이 배치들 모두, 운전자의 정보 처리를 용이하게 했고, 주행의 신체적 부담을 감소시켰다. 이러한 이점을 갖는 CMS 디스플레이 배치의 설계 특성은 CMS 디스플레이들을 운전자의 정상 시선에 가깝게 위치시켜 시선의 이동 거리를 감소시키면서, 좌우 CMS 디스플레이를 각각 운전자의 좌우 측에 놓아 양립성을 유지하는 것이었다.

주요어: 헤드-업 디스플레이, 유경험자, 정보 요소의 중요도, 정보 사용 상황, 설계 개선점, 카메라 모니터 시스템, 차량 내 사이드-뷰 디스플레이, 디스플레이 배치, 정보 처리, 신체적 부담

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