Distraction and Driving Behavior by Presenting Information on an "Emissive Projection Display" Compared to a Head-up Display

Verena C. Knott(✉), Stefan Demmelmair, and Klaus Bengler

Faculty of Mechanical Engineering, Institute of Ergonomics,
Technische Universität München, Boltzmannstraße 15,
85747 Garching bei München, Germany
{knott, demmelmair, bengler}@lfe.mw.tum.de

Abstract. A study in the static driving simulator examines whether the use of an Emissive Projection Display (EPD) causes significant effects on attention and cognitive load in addition to the driving task. Moreover, a comparison with a conventional Head-Up Display (HUD) is drawn. Conclusions regarding the driver's stress resulting parallel to the driving task are objectively determined by reaction times that are needed to perform a visual secondary task. The results of the analysis of objective data show significant extensions in the response times the performing the secondary task for the EPD, compared to HUD. Also data for the subjective assessments of workload during the different test runs are discussed.

Keywords: Driver assistance system · Emissive projection display (EPD) · Head-up display (HUD) · Reaction time · Distraction · Workload

1 Introduction

Numerous information assistance systems are installed in vehicles of the medium or luxury class. Such support systems are for example, head-up displays (HUDs), which allow displaying information for navigation or speed directly in the driver's field of view while driving. In addition to conventional HUDs, which images can be seen about 2 m in front of the driver, just above the engine hood, there are also so-called contact-analog HUDs. These systems present the information correct on location [1]. These display concepts also have the advantage that the duration of eyes off the road is reduced [2]. However, this concept is not consistently used and the size of the display area is limited to one position. Due to this, a new approach deals with a similar presentation of information. The difference is that the information is directly displayed into the windshield surface on the inside. This display concept which in the literature is also called "Emissive Projection Display" (EPD) can be realized in the following way (see also [3]): The EPD system in the driving simulator laboratory of the Institute of Ergonomics at the Technische Universität München (TUM) has two complementary components. An ultraviolet laser (KVANT, customized system) and a fluorescent film (SuperImaging™) coated on a plexiglass windshield, which is activated by the laser beam at an appropriate wave-length of 405 nm to illuminate.

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As part of a driving simulator study at the Institute of Ergonomics the effects of a windshield display on the driver's attention on the road and on the driving behavior were investigated in comparison to a conventional HUD.

2 Research Questions

Since no studies exist on the investigation of distraction as well as readability of information shown on a windshield (WS) and previous findings resulting from studies of Head-Up Displays (HUD) are not transferable to the Emissive Projection Display (EPD)-technology, following research questions are being considered:

1. **Which differences are observed regarding the driver´s distraction between using the Head-Up Display and the EPD-technology?**

It is assumed, there is a difference regarding the driver´s distraction between the two display concepts – the simulated HUD and the EPD-technology. The HUD projection as well as the driving scenery of the simulation are shown on the same screen. The alternative display concept projects the information directly on the windshield and the driver´s eyes have to look at the windshield. This affects comfort as well as time for perception of the information. The reaction time of the visual secondary task´s execution is used as a parameter for measuring the distraction. So it can be determined how much time the participants need for the perception and execution of the secondary task.

2. **Is there a connection between the driving behavior and the use of the information presented on the Head-Up Display as well as on the windshield?**

It shall be demonstrated, that the two different display concepts have an influence on the driving behavior. It is postulated that the performance of the secondary task depends on whether there is additional information displayed to the driver and how it is presented. The driving behavior of each test person can be measured as well as compared, by means of the mean deviation (MDEV). It is assumed that the mean deviation differentiates between the various test drives in the main study (without secondary task, secondary task with simulated HUD as well as secondary task with EPD-technology).

3. **Which difference exists between the test person's subjective assessments with respect to the usability of the two different display systems?**

It is assumed the test persons assess the two display concepts differently as to their usability. The two concepts differ with respect to the distance to the object display which affects the visual accommodation ability. But also the type of presentation is different: The simulated HUD projection is displayed as objects in the driving scenery on the wall screen, whereas the laser projection glows on the fluorescent film which is affixed on the windshield.

4. **Which workload exists for the test candidates by using the information visualized on the windshield compared to the simulated HUD?**

A further postulate of this study is that the subjectively determined Overall Workload Index (OWI) differs between the two display systems. As already mentioned in research question 3, the display concepts differ in distance as well as in their mode of presentation. Thus this also takes influence on the workload.

3 Method

3.1 Test Environment

The used experimental setup is shown in Fig. 1 with a test participant wearing laser safety glasses.

Fig. 1. Experimental setup with components and a test participant with laser safety glasses (6)

The setup consist of a seating box with a driver´s seat, a Plexiglas windshield (1), a projection screen, a video projector, a Spectrum eLite 1.6 W laser projector (2, KVANT), a 7″ TFT touch screen monitor for the display of the speedometer (3) and a PC. The task of the PC is to calculate the virtual driving environment with the simulation software SILAB (Version 3.0, WIVW GmbH). Furthermore the steering wheel (4), pedals (5) as well as the video projector are connected to the PC. For the communication between the driving simulation and the laser projector, the network with the User Data Protocol (UDP) is used.

The objects of the visual secondary task for simulation of an ordinary head-up display are presented directly in the driving simulation as a texture. The driving environment with its textures is shown on a wall screen 3.65 m away from the participant's eyes.

The display on the windshield is implemented by the Emissive Projection Display (EPD)-technology according to [3] and contains an ultraviolet laser and a fluorescent film which is mounted on the windshield. The ultraviolet laser beam activates the fluorescent film and makes the film light up at this precise spot. Due to the fact that the laser passes the given vector graphic 60 times each second, the human eyes perceives the projection as a static image.

3.2 Lane-Change-Task (LCT)

To assess automotive systems, generally – as in this study – dual-task methods are applied [4]. Using the standardized driving task "Lane Change Task" (LCT) according to (ISO 26022: 2010) [5] and a visual task, a statement regarding the impact of information presentation of the two display concepts to humans is possible.

In this study, the LCT is the primary task and it is used to assess driving performance when different objects are shown either on the screen or directly on the windshield which the driver has to identify. During the LCT a test participant is required to drive at a constant, system controlled speed of 60 km/h along a simulated straight 3-lane highway and about a 3000 m long section of that road. Participants have to change the lane fast and precisely at regular intervals. Signs on both sides of the road appear 40 m before passing them and instruct the test participant which lane has to be taken.

3.3 Visual Task

In addition to the primary task there is a visual task to detect the direction of the opening of a Landolt ring shown. A Landolt ring is a circular ring with an opening. The position of the opening varies. Exact dimensions of the rings comply with DIN EN ISO 8596: 2009 [6]. The reason why only the contour is displayed on the windshield as well as on the wall screen can be traced back in passing the vector graphic by the laser. Due to the fact the reflecting light of the fluorescent film has a blue color, the Landolt rings are displayed in the simulated Head-Up Display in blue as well (hex color code: #0000CD). The size of the rings is designed by means of the DIN EN ISO 15008: 2009 Standard [7] depending on the viewing distance. The rings with the four possible opening directions are shown in Fig. 2.

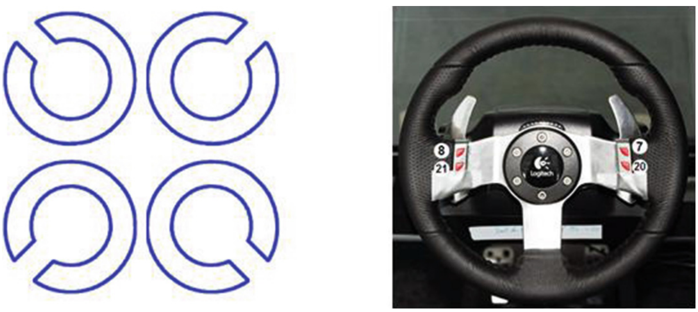

Fig. 2. Left – Landolt rings and the choices in the hole; Right – steering wheel and buttons

The Landolt rings are projected by means of a laser (EPD-technology) as well as displayed as a texture during the driving simulation (HUD). Both the opening direction and the interval between the inserted rings vary.

Below the secondary task of the driver is explained in detail. As soon as a Landolt ring is shown, the test person has to detect the right position of the opening and push the corresponding button on the steering wheel as quickly as possible. Four buttons on the steering wheel are used for the detection and are also shown in Fig. 2. The time elapsed between the first appearance of the Landolt ring and the detection is recorded. This aspect makes it possible to measure the reaction time objectively which was needed to perform the visual task.

According to the "Human Processor"-Model [8] the time frame is defined for a valid hit. In the following the steps performing the secondary task are outlined. The relevant processors according to [8] are parenthesized.

Step 1: Focusing on the randomly appearing Landolt ring (perceptual processor)
Step 2: Recognizing the opening of the Landolt ring (perceptual processor)
Step 3: Determination of the corresponding button (cognitive processor)
Step 4: Pressing the button on the steering wheel (motor processor)

In the following, this information can be used to calculate the range in reaction time t according to [8]:

$$t = 2\tau_P + \tau_C + \tau_M \tag{1}$$

t: reaction time [ms]
τ_P: time frame for one perceptual process cycle [ms]
τ_C: time frame for one cognitive process cycle [ms]
τ_M: time frame for one motor processor cycle [ms]

In accordance with signal detection theory a hit is valid when the correct button is pushed between 300 ms and 3000 ms after first appearance of the Landolt ring. When no button is pushed the Landolt ring removes itself after 3000 ms.

There are four possible occurrences for pushing the button which are explained below: Hit, Miss, Fail and False Alarm.

- Hit: The test person has detected the correct opening of the ring and pushed the corresponding button on the steering wheel between 300 ms and 3000 ms after the ring's first appearance
- Miss: No button was pushed
- Fail: The wrong button was pushed between 300 ms and 3000 ms after the first appearance of the ring
- False Alarm: Either the test person pushed earlier than 300 ms (deception) or later than 3000 ms

For the interpretation of the size of the Landolt rings depending on the viewing distance, the DIN EN ISO 15008: 2009 Standard [7] is used.

3.4 Test Procedure

The study was conducted in the driving simulator of the Institute of Ergonomics (TUM) described above. Experimental protocol with a check list, explanations as well as instructions are prepared in advance. This ascertains to have a standardized procedure and equal conditions for all participants.

At the beginning, the participants are informed about the study and personal data is collected with a demographic questionnaire. After this, a familiarization run is driven where the Landolt rings are displayed on the windshield. So the test person gets a feeling for the route, the actuations with the buttons on the steering wheel and the primary and secondary task.

After that the preliminary study begins. The participant only processes the secondary task without driving. The secondary task is carried out by using both, the EPD-technology and the simulated HUD. The order of the two tasks is at random. Although the test person does not drive, a screenshot of the driving environment is displayed on the wall screen. The reason for this is that you always have the same conditions and the ability to compare amongst the results of the preliminary, main and post study.

Subsequently the main study starts. It contains three different Lane Change Task (LCT) runs. During the so called Baseline-drive (BL (LCT)) the person only drives the Lane Change Task-course without a secondary task. Two more LCT-drives follow. In the onetime part, the participant drives the LCT-course and the secondary task is shown on the wall screen (BL(LCT) + HUD) and in the other time the secondary task is displayed on the windshield (BL(LCT) + WS) by means of the EPD-technology. Again all three runs of the main study are performed at random.

Last the post study is executed which is performed the same way as the preliminary study.

Apart from recording objective data, such as driving behavior and reaction time in the secondary task, also subjective data is collected. After each run of the main study, each participant answers the NASA TLX (NASA Task Load Index) questionnaire. The NASA TLX is a subjective, multidimensional assessment tool and is introduced to measure the Overall Workload Index (OWI) [9, 10]. This index composes mental demand, physical demand, temporal demand, performance, effort and frustration.

In addition to the NASA TLX, the System Usability Score (SUS) is also used after each run with the completion of the secondary task during the main study. The SUS is a simple tool to measure the usability of the two different display modes [11].

In Fig. 3, a test person is presented with a projected Landolt ring on the windshield during a test drive.

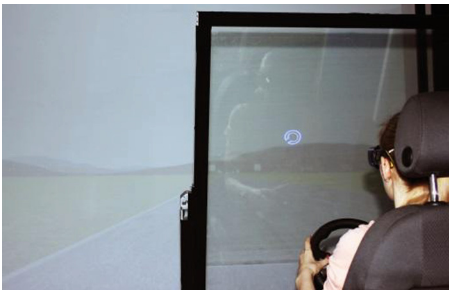

Fig. 3. A test person with a projected Landolt ring on the windshield during a test drive

4 Data Collection and Statistical Data Analysis

4.1 Objective Data

To determine the driving performance of each participant, the average deviation (MDEV) is calculated for each run in the main study. The definition of the MDEV is the area between the normative model and the participant's actual driving course, divided by the course length. So there is an objective measure to compare the driving skills between the test persons.

For the MDEV calculation the x- and y-coordinates of the car has to be known as well as the positions of the signs for the lane change. From this, the normative model can be calculated, followed by the determination of the MDEV for each run.

For the secondary task, the reaction time between the first appearance of the Landolt ring and the button actuation has to be determined. Furthermore it is necessary to know which button was pressed. Finally there is a time interval set between 300 ms and 3000 ms after the first appearance of the sign for a valid hit. It was calculated by human reaction time. For the determination of the reaction time and the number of correct hits, the time stamp of the buttons pressed as well as which one of the buttons is recorded. Furthermore the time of the appearance of the ring and its opening direction is also recorded for the subsequent analysis.

The objective measurement data for driving behavior is based on the recorded data of the simulation software SILAB (WIVW GmbH, Veitshöchheim, Germany). During the experiment SILAB records the general simulation data (simulation time, time of displaying the Landolt ring), dynamic driving variables (speed, vehicle distance to the right edge of the roadway) as well as the recorded steering wheel operation (keystrokes) as a plain text file in ASCII characters. By using the recorded time from the beginning of displaying the Landolt ring as well as the time when pressing the button, conclusions regarding the reaction times of the subjects can be drawn. The plain text file can be opened with an ordinary text editor (Crimson Editor, Notepad) and assessing programs such as Microsoft Excel or MATLAB MathWorks.

4.2 Subjective Data

In addition to the objective data, subjective measurement data is recorded for the analysis of the test drives. The NASA Task Load Index (NASA TLX) questionnaire and the System Usability Scale (SUS) questionnaire are used.

The NASA TLX questionnaire was developed by the Human Performance Group at the NASA Ames Research Center. This standardized questionnaire is a subjective, and a multi-dimensional measuring method, to detect the workload under different test conditions [9, 10]. For the comparison of subjective assessment for the workload of the individual test runs, the Overall Workload Index (OWI) is used. The OWI is the result of each test run in the unweighted version of the summation of the individual ratings, divided by the number of dimensions (6) [9]. The System Usability Scale (SUS) questionnaire of [11] is used to subjectively evaluate the usability of a system. Usability is the multidimensional property of a system that rates the interaction between user and system [12].

5 Results and Discussion

5.1 Participants

The study involves 21 participants. More than three quarters of all test subjects are male (76 %). Also, more than three quarters of the participants are between 26 and 35 years old (76 %). The youngest participant is 24 years, the oldest 70 years old ($M = 31.95$, $SD = \pm 10.85$). More than 90 % of all participants had experience with a conventional head-up display, a contact-analogue head-up display or even gained experience with both display concepts. Furthermore, 57 % of the participants needed a visual aid and one subject had a red-green color blindness. None of the subjects had a relevant ocular disease.

5.2 Objective and Subjective Results Regarding the Distraction and Mental Workload

The aim of this study is, to determine the effects of a concept that projects information using a windshield for the driver's attention and on the subjective assessment of workload in comparison to an ordinary head-up display. The objective average response time for the processing of the visual secondary task and the driving behavior are used for the objective data, while the Overall Workload Index (OWI), the subjectively-perceived workload, has been used for the subjective statement.

Objective Data. The objective data recorded for the secondary visual task – time for selecting and pressing the appropriate button – was evaluated according to the signal detection theory. The participants needed an average response time of $M_{RT,\ HUD} = 943.42$ ms ($SD = \pm 123.16$ ms) for processing of the visual task in the simulated HUD. For the condition on the windshield, the average reaction time of the subjects was $M_{RT,EPD} = 1075.82$ ms ($SD = \pm 117.55$ ms). To test the significance with respect to the hit reaction time between the two experimental conditions – HUD and EPD – a t-test (two sided, paired) was used at a significance level of $\alpha = 5$ %. The test shows there is a significant difference in the response times for the two different concepts (LCT + HUD and LCT + WS: $t\,[20] = -5.4851$, $p = 0.000023 < 0.05$). The reaction time for processing of the visual secondary task is significantly higher when displaying the Landolt rings on the windshield using the EPD technology (see Fig. 4). This indicates an increased mental workload in the test condition with information on the windshield.

The driving behavior is measured by the average track deviation (MDEV), which is shown in Fig. 5 for the individual runs.

The study conducted in SPSS one-way analysis of variance with repeated measures (ANOVA) for a 5 % significance level indicates there is no significant difference in the MDEV and consequently in the driving behavior in the three mentioned test runs: $F\,(2, 38) = 2.599$, $p = 0.088 > 0.05$.

Subjective Data. In the simulation run, the OWI has an average value of $M_{OWI,\ HUD} = 30.71$ ($SD = \pm 14.18$) with the presentation of information in the HUD, and in the EPD condition an average value of $M_{OWI,EPD} = 27.66$ ($SD = \pm 13.55$). The implementation of a t-test (two sided, paired) shows that the subjectively assessed

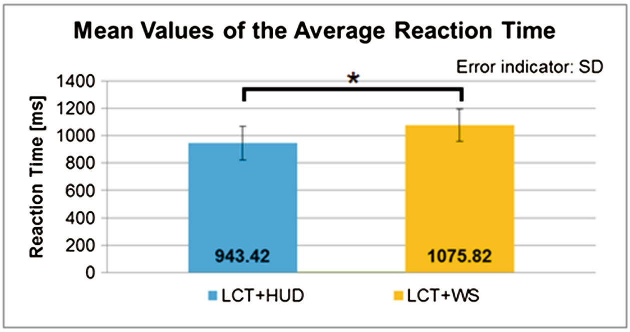

Fig. 4. Mean values of the reaction time [ms] of the test runs with visual task

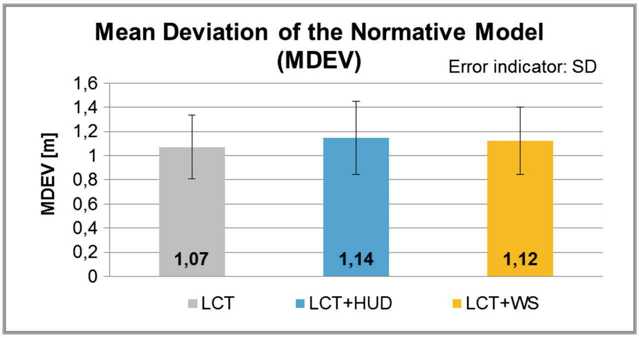

Fig. 5. Driving behavior in the different test runs

workload during the test run with information presentation on the simulated HUD is significantly higher in comparison to the condition presenting the information on the windshield (LCT + HUD and LCT + WS: $t[20] = 2.10$, $p = 0.049 < 0.05$). Figure 6

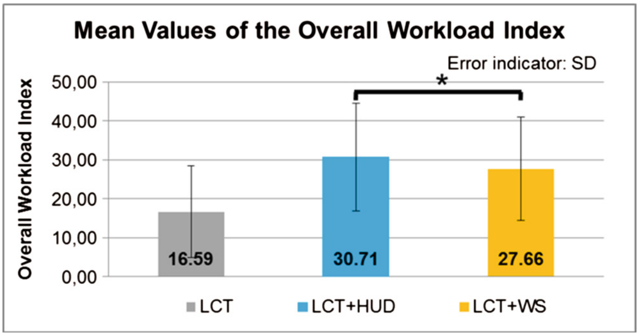

Fig. 6. Subjective ratings of the mental workload in the individual conditions

also shows the comparison to the test run LCT, where only the driving task has to be conducted.

5.3 Subjective Results Regarding the Usability

The analysis of the usability of the system using the System Usability Scale and t-test results with no significant difference (LCT + HUD and LCT + WS: t [20] = −0.039, $p = 0.97 > 0.05$). According to [13] both concepts can be regarded as 'good' (Fig. 7).

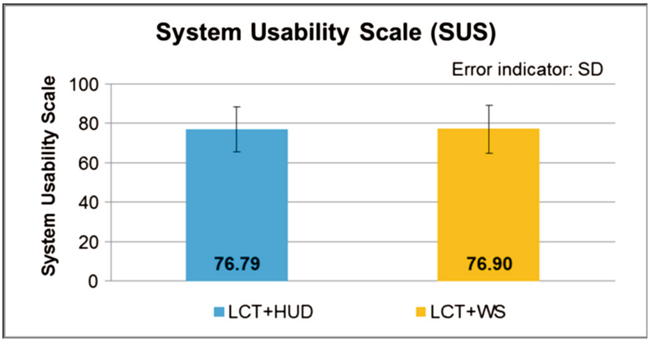

Fig. 7. Average value of the SUS-score of the two concepts displayed

6 Conclusion

Related to the significantly longer reaction times for the visual task on the windshield compared to the simulated HUD it can be concluded, the information presentation on the windshield requires a longer time for recording and editing as a presentation of information in the HUD. This can be attributed to the accommodative capacity of the eye. While the driving scenery and the rings are on the same accommodation level in the simulated HUD, the driver must first focus on the windshield when using the EPD technology. This dynamic adjustment of the eye takes time. Worth mentioning is also the fact that the average age of the subjects collective is relatively low and the ability to change between different focus levels decreases with age [14]. Nevertheless, the next step is to investigate the difference between symbols and text information as well with their impact on the driver.

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