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HEADSLAVED DISPLAYS IN A DRIVING SIMULATOR

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ABSTRACT

In a driving simulator we examined how various types of head slaved displays influence driving performance. The following display conditions were compared: 1. Wide projection screen; 2. Head mounted mask with limited field of view; 3. Head Slaved Display (HSD) projected in the viewing direction (discretely); 4. HSD projected in the viewing direction (continuously); 5. Head Mounted Display (HMD) in see-through mode; 6. HMD without own-vehicle references; 7. HMD with computer generated own-vehicle references. The simulator collected data on the driving behavior. We conclude that: 1. An HMD has negative effects on driving performance. The cause is not the limited field of view but, probably, its large weight and the considerable image delay. 2. A continuously head slaved window is a good alternative for projection on a large screen. 3. If an HMD is used it is recommended to apply vehicle references in the generated out-world image.

INTRODUCTION

Driving is a task that relies heavily on visual information, and the driving environment can be very complex. At high speeds, relevant details in the environment are often observed from large distances. Furthermore, the driver has to look in many different directions to obtain relevant information. These combined factors result in very high demands on the visual images presented in a driving simulator. A driving simulator therefore generally requires a large (e.g. 180 x 50 deg), high-resolution multichannel display system. The high costs associated with image generation have been a major hurdle for developing cost-effective driving simulators for driver training. Since a driving lesson on the real vehicle is relatively cheap, a driver trainer has to be cheap as well. In this paper we will explore several possible solutions that reduce image generation cost in driving simulators.

One commonly used method to reduce image generator cost is to present a relatively small computer generated image in the direction the driver is looking using a Head Slaved Display (HSD). In this way, an HSD can provide a large field of regard with only a small instantaneous field of view. The direction in which this field is presented is coupled to the orientation of the head by means of a head tracker system. The image may displayed by either a Head Mounted Display (HMD), or an array of monitors. With an HMD a horizontal field of regard of up to 360° may be obtained, while the instantaneous horizontal field of view ranges from 25° to 65° for the most common types of HMD. With a horizontal array of five monitors, typically an instantaneous horizontal field of 40° is obtained, with a horizontal field of regard of 200°. In it most simple form the image jumps discretely across the monitors, depending on the direction of the observer's head. It is apparent that the savings with these type of HSD's, compared to a wide-field projection system, may be considerable: one image generator instead of five, and a compact display setup. An intermediate HSD solution is a wide-field projection system with a window that continuously follows head motion. Only one image generator is required in this case.

Little is known on the effects of the use of an HSD instead of wide-field projection on the validity of driving simulation. Kappé (1997) studied the effects of HSD on straight road driving in a simulator. A continuously head slaved window of 50°H was presented on a projection screen. With the head slaved window the lane-keeping performance slightly decreased when compared with a display with a wide field of view. Continuous window motion gave worse lane keeping than discrete (one channel at a time) window motion. Vehicle references (the image of the hood and window stiles) in the scene, which in principle gave information on vehicle rotation in distinction to head rotation, did not alter performance.

Van Erp and Kappé (1977) studied the effects of HSD on curve driving performance in a simulator. The HSD was a continuously head slaved window of 40°H presented on a projection screen of 156°H. They found that performance with HSD was hardly different from full field performance, if no vehicle reference was used. Surprisingly, the use of vehicle references decreased performance, whilst the difference between HSD and full field disappeared. A possible explanation for this is that the image of the car's hood in the vehicle reference condition obscured the road, and thus the course of the curve immediately in front of the driver.

There are various reports on the effects of restricting the instantaneous field of view on real driving. Pepper (1986) measured performance on a slalom test course. He found no difference, compared with full field, when an instantaneous field of 60° H was applied, created by wearing a head-mounted mask. Spain (1988, 1991) found similar non-effects of a field restriction of 40°horizontally. On the other hand, Wood and Troutbeck (1992) found that performance of various tasks on a curved driving course was significantly affected by limiting the instantaneous field to 40°H and V by means of a head mounted mask. According to Wood and Troutbeck (1994) even instantaneous field restriction to 90° H and V results in slower driving.

From the above it appears that literature does not give unambiguous information on the effects of a HSD in car driving. In the present study, a driving simulator was equipped with various types of HSD's: a head slaved window and an HMD. The head slaved window was presented on a projection screen, and it either discretely or continuously followed horizontal head motion. In the HMD condition, the presence of vehicle references was varied in three levels: absent, present in the computer generated image, and the actual vehicle references in see-through mode. Seeing vehicle references is of theoretical importance, because these provide unambiguous information on the vehicles position and orientation with respect to its environment, in clear distinction to the direction of the viewing window (De Vries and Padmos, 1997; De Vries and Padmos, 1998; Van Erp, 1995). Without special precautions, in an HMD no vehicle references are present. In the conditions with the projection screen, the car's hood, steering wheel and window stiles were visible to the subject sitting in the vehicle mock-up.

For each display condition, driving performance of experienced drivers was measured and compared to a wide field projection display. The main driving task consisted of making a right or left turn on a crossing road, while merging in a traffic stream on that road. Head movements up to 90° left or right were required to detect the gap in the crossing traffic stream. This is a critical condition for HSD's. The following chapter provides a detailed account of the methods used.

METHODS

Apparatus

The subjects were seated in a Volvo 240 automobile mock-up, in the center of a cylindrical projection screen (radius 3.75 m) of 160° wide and 30° high. To increase the side view on either the left or right hand side to 100°, the vehicle mock-up could be turned 20° left or right using the moving base. The motion base was not used to provide mechanical motion feedback. The projection screen, with four video projectors (Barco graphics 800) was used for some of the display conditions; for other display conditions a Helmet Mounted Display (N-Vision Datavisor HighRes) was used (see Section Display Conditions). Horizontal head motion was registered with a Polhemus Fastrac head tracker. Of the image generator (ESIG 2000) one to four channels were used, depending on the display condition. The dynamic vehicle model was based on the Volvo 240, with automatic gearshift. The simulator recorded the vehicle's position and orientation with respect to the road, and the subject's horizontal head direction, with a sampling rate of 10 Hz.

Task

The subjects drove on rural roads, widths 5 and 7 m, with central and side road marking, surrounded by trees. Speed was limited to 50 km/h. After driving a straight section of 200 m, the driver had to stop the car for a crossing, at a point marked by a transverse road marking. On the crossroad a traffic stream passed with 50 km/h. The subject's task was to detect a gap in the stream and to pull up while taking a left or right turn onto the crossroad, merging in the stream. The gap occurred at unpredictable moments, and was wide enough (110 m) to allow safe merging. Except for the gaps the spacing of the cars in the stream was 20 or 60 m, distributed randomly. For right turns the traffic stream came from the left; for left turns the stream came from the right. A collision with a car in the stream, due to selecting a too narrow gap or due to not pulling up fast enough, was accompanied by a realistic collision sound. During the straight sections, subjects had to maintain a lateral distance to the road edge of 40 cm. A light side wind was simulated through a low frequency noise on the steering action. (This noise was a composite of sinuses with maximum frequency of 0.15 Hz, with maximum amplitude of 6°). The turns had to be taken such that the car was as soon as possible at the target distance from the road edge again, in the correct orientation. The rounding-off radiuses on the corners between roads varied between 8 and 14 m.

For each of the five replica's per display condition, each subject drove four runs consisting of a straight road segment, followed by a stop, turn and merging in the same turning direction (left or right turn). Then the platform with the mock-up was turned (see next Section), and he drove four runs straight -- stop -- turn -- merge in the opposite turning direction.

Display Conditions
Seven different displays were evaluated in the experiment.

1. *Full Screen.* In the full screen condition the computer generated image was projected on the full screen width (160°H × 30°V). The performance in this condition served as a baseline to compare the performance in the HSD conditions. This condition is shown in Figure 1.

Figure 1, an overview of the driving simulator in the full screen viewing condition

There were six HSD conditions:

2. *Head Mounted Mask*. Using a spectacle frame, tubes were mounted on the head. These tubes were mounted with rectangular viewing apertures at 8 cm from the eyes, see Figure 2. This limited the instantaneous field of view to 38°H × 30°V, which is identical to the field of view of the HMD. This may be seen as a simulation of a perfect HMD. Perfect because there are no optical problems, there is no delay, and its mass is very low.
3. *Head Slaved Window Discrete*. The image was restricted to a window on the projection screen, with size 39°H × 30°V (similar to the field of the HMD). The window appeared at four discrete horizontal positions, depending on the orientation of the subject's head (yaw angle only). Thin black lines were positioned between the windows, thus imitating a display that consists of an array of four monitors (39°H x 30°V), set up as an arc of 160° around the observer. The computer generated image is presented on one of the 'monitors' at the time, and changes between monitors are discrete. Great care was taken to assure that the delay of the active window equaled the image delay. Therefore the images presented a stable virtual environment.

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Figure 2, The mask that was used to simulate a 'perfect HMD'

4. *Head Slaved Window Continuous*. A similar system as the Head Slaved Window Discrete, but with a window (39°H × 30°V) that continuously followed the yaw angle of the observers head, see Figure 3. Again great care was taken to assure that window delay equaled image delay, and a stable virtual environment was presented.

Figure 3, the head slaved window continuous. In this display mode, the virtual environment is perceived to be stable when changing the viewing direction

The next three display conditions used an HMD (viewing angle 39°H × 31°V, identical images for each eye). The image of an HMD has a delay equal to the sum of the head tracker and image generator delays. The total delay was

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190±10 ms (tracker ±33 ms, simulation models 33 ms, image generator 115 ms). It is known that this delay is much to high for the perception of a stable virtual environment using an HMD (it is estimated that image delay should be < 10-20 ms REF). The delay values that were measured in the present setup are in the range of most HMD systems.

5. *HMD With See-through References*. The HMD was used in see-through mode (Figure 4), and by adapting the lighting of the simulator room the silhouettes of the steering wheel, the car hood and the window stiles could directly be observed when wearing the HMD. The virtual environment was transparently visible over the vehicle references, be it that its contrast was reduced.

Figure 4, the head slaved display in see through mode

6. *HMD Without References*. The HMD was used in its normal mode. There were no vehicle references presented, and only the virtual environment could be observed,.
7. *HMD With Generated References*. With the HMD in its normal mode, the virtual environment now also included a silhouette image of steering wheel, hood and window stiles that represented the vehicle references of the driving simulator.

A summary of the display conditions is presented in Table 1. For each condition is marked which image aspects are influenced by the image delay with respect to head motion, measured to be.

Table 1, Summary of display conditions, with Delay with Respect to Head Motion

	Delay (ms)		
Display Condition	**Vehicle Reference**	**Window**	**Image Content**
1. Full Screen	--	--	--
2. Head Mounted Mask	--	--	--
3. Head Slaved Window Discrete	--	190	--
4. Head Slaved Window Continuous	--	190	--
5. HMD With See-through References	--	--	190
6.HMD Without References	--	--	190
7. HMD With References Generated	190	--	190

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Subjects and Procedure

12 paid university students participated as subject. All had a car driving experience of over 10 000 km and age was between 20 and 27 year (mean age 22.8 y). Subjects participated in pairs, during one day per pair. Before the experiments they were tested on vision and hearing. All subjects passed the tests, which means: they had visual acuity >1 on both eyes (TNO Landolt C test); they had stereo vision (Titmus Fly test); they could discriminate sounds coming from left or right (handclasp test).

Each subject received written general instructions on aims and procedures of the experiment and on the driving task. After that he received per display condition an explanation of the display and drove five successive series (replicas) of eight runs in that condition. The first replica of each condition was a training replica in which the subject received continuous automatic auditory feedback on his lane error (left or right loudspeaker beeps warned for a right or left lane deviation over 25 cm from the ideal path). Additionally, the subject received from the experimental supervisor corrections on obvious errors in the merging task.

Conditions were approximately order-balanced across subjects, but because limitation of changing time was wanted the three HMD-conditions were always following each other. Also, order of left and right turns was balanced. One replica lasted about 5 minutes. When one subject drove the five replica's per condition, the other rested.

At the end of a series of 5 replicas the subjects were interviewed per condition about possible difficulties or discomforts they experienced and how they tried to cope with it.

Dependent Variables

Table 2 summarizes the dependent variables. These variables were calculated from data sampled by the simulator supervisor, per subject, per display condition, per replica, per left or right turn on merging, per road segment.

Table 2, Dependent Variables

SYMBOL (unit)	Name	Explanation
LANESD (cm)	SD of lane error	SD (standard deviation) of lateral distance (only for straight road sections)
HEADSD (°)	SD of heading	SD of vehicle heading with respect to road. (for straight sections) is a measure of course stability. Ideally, heading=0.
TURNPOS (cm)	Lateral position error After turn	Lane error from target curb distance (absolute value), immediately after each turning section
COLLISION	Conflicts with traffic	Number of merges for which one or more collisions with crossing traffic occurred
MISGAP	Missed traffic gap	Number of stops after which one or more gaps in the traffic stream were missed before merging
VIEWSPEED (°/s)	Speed of head rotation (yaw angle)	Mean absolute speed of subjects' horizontal head rotation, measured during driving in turning sections

Statistical analysis

Analyses of Variance were performed with the package Statistica 5.1 (repeated measures design per subject), separately for each dependent variable. For most dependent variables, the statistical design was as follows:

Subject (12) × Display Condition (7) × Turning Direction (2) × Replica (4, omitting the training replica). Before each analysis, outliers were removed. A cell was considered an outlier if it was clearly outside the cumulative frequency distribution of the whole set of data for that particular dependent variable. If there was a significant effect of an independent variable (p # 0.05), a Tukey post-hoc analysis was performed to study which levels of the variable differed.

RESULTS

Absent or Small Effects

The effects of replica (omitting the first training trial) were not significant or, at best, small. Moreover, interactions Replica × Display Condition were also absent or small. The variables COLLISION and MISGAP did not show any effect. This was also due to the small numbers: collisions occurred in 1% of the runs; gaps were missed in 0.3% of the runs. Apparently, the merging task was performed adequately.

Driving Straight

In Figure 5 the significant effect of display condition on the SD of the vehicle heading is depicted ($p < 0.0001$). According to post-hoc analysis, the conditions without HMD give no mutually different HEADSD. All HMD conditions give significantly larger course instability than the conditions without HMD ($p < 0.005$ to $p = 0.0001$). Mutually, the HMD conditions differ significantly. The largest HEADSD is obtained with HMD without references and the smallest instability is with HMD with references generated.

The effect of display condition on LANESD, the standard deviation of the lateral position, is comparable to the effect on HEADSD, be it that some differences between conditions are less outspoken.

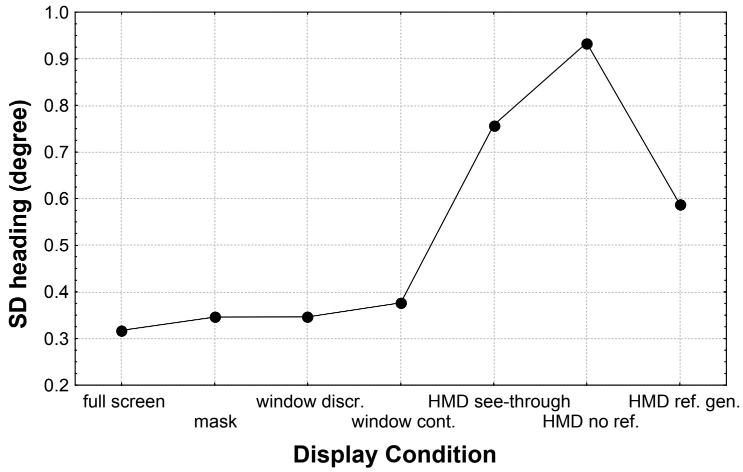

Figure 5. The effect of display condition on the standard deviation of heading direction (straight sections). With an HMD lanekeeping performance is poor. HSD and full screen allow similar performance.

Turning Behavior

The effect of display condition on TURNPOS, the lateral position error (absolute value) immediately after turning, was significant ($p < 0.0001$), as is the interaction Display Condition × Turning Direction. This interaction is shown in Figure 6. Post hoc analysis revealed that for turning right the effect of display condition on TURNPOS was not significant. For left turns, the conditions without HMD showed neither mutual differences nor differences with the right turn performance. However, all HMD conditions gave for left turns a significantly worse performance than the conditions without HMD (p # 0.002), except for the difference between head slaved window continuous and HMD with references generated, which showed only $p = 0.07$. Please note that values of TURNPOS, especially for left turns, are over 4 times larger than LANESD, which was defined for straight sections. This indicates a sloppy turning behavior.

Viewing Behavior in Turns

The effect of display condition on VIEWSPEED (mean absolute speed of head rotation in turning sections) was significant ($p = 0.0002$). For this variable also the interaction Display Condition × Turning Direction is significant ($p = 0.0006$).This interaction is shown in Figure 7.

According to post hoc analysis, the effect on VIEWSPEED is not significant for turning right. For left turns, the only mutual difference for the conditions without HMD is that with head mounted mask VIEWSPEED is slightly larger than with the two head slaved window conditions ($p = 0.01$). The HMD conditions give lower head speed than without HMD ($p = 0.01$ to $p = 0.0001$), except for HMD without references, which does not differ significantly from the two head slaved window conditions. Among the left turns with HMD are no differences.

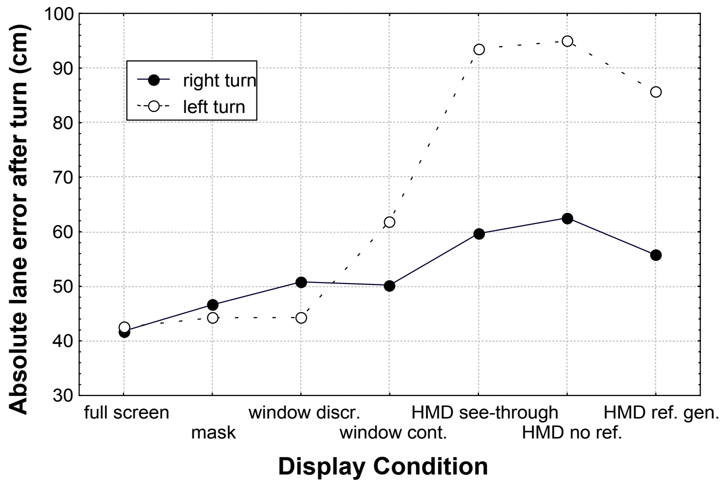

Figure 6. The interaction of Display Condition × Turning Direction for TURNPOS.

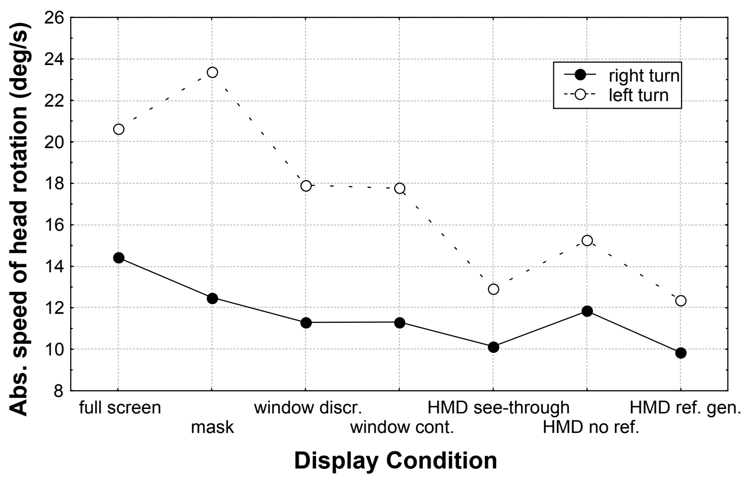

Figure 7. The interaction Display Condition × Turning Direction for VIEWSPEED.

DISCUSSION

General driving behavior

For straight driving this easy task without HMD is corroborated by the low mean value of the objective parameter LANESD, the SD of the lateral position. Comparison with Riemersma (1987) indicates accurate behavior without HMD. The fact that HEADSD, the standard deviation of the vehicle heading, was almost twice as large as found by Riemersma (1987) for normal straight road driving, may be caused by the absence of mechanical motion feedback in the simulator. Kappé et al. (1997) found for HEADSD much higher values, up to 1.3°, but he used a joystick to control the vehicle instead of a steeringwheel.

The generally low values of COLLISION and MISGAP means that subjects performed the gap detection and merging part of the driving task well, irrespective of the display condition. The operator's observations of subjects' viewing behavior, revealed that many subjects developed a gap detection strategy that minimized head motion. When a gap was detected in the approaching traffic stream, subjects memorized the color of the car preceding the gap and then looked straight ahead until that car passed and they could merge. This is not like the behavior in real driving; the present behavior is a logic consequence of the expectation that the gaps, once detected, would keep their size.

The turning performance was very inaccurate, as shown by the high values of TURNPOS. One probable cause is that in this experiment unlike in real driving, the steering wheel does not automatically return in its neutral position if released at the end of a turn. Maybe also the absence of stereo vision causes the subjects to have a less accurate estimate of the course of the turning path.

TURNPOS showed for left turns a larger lateral position error immediately after the turn than for right turns. This is not surprising, because taking right turns is like tracking the curved right curb, while taking left turns correctly requires more a correct internal representation of the total geometry of the crossing. Indeed, often subjects commented that turning left was more difficult. Higher values of the head motion parameter VIEWSPEED for left turns compared to right turns in the conditions without HMD point in the same direction.

Differences Between Display Conditions

Effects of HMD vs. non-HMD. The general conclusion that emerges from the dependent variables that showed an effect of display condition is that the conditions with HMD were found more difficult and gave a worse performance than the conditions without HMD. At the same time, differences between Full Screen and the other conditions without HMD but with restricted simultaneous field of view are hardly ever apparent. This means that the restricted instantaneous HMD field can not be the cause for its deficiency.

The variable VIEWSPEED shows that head motion in the display conditions without HMD was much larger for left turns than for right turns, which is in accord with the turning left task requiring a more general view of the crossing than turning right. However, with HMD this difference between turning left and right is considerably smaller. It may be concluded that the HMD suppressed the larger required head motion for turning left. There are three possible causes why head motion is suppressed in an HMD: 1. image smear, especially in an HMD with LCD displays; 2. image delay, causing a wiggling image with head motion; 3. the mass inertia of the heavier HMD's. De Vries and Padmos (1997), who compared in a flying task Head Mounted Mask, Head Slaved Window, and HMD, did hardly find effects of display type on head motion. They used a HMD (Virtual IO i-glasses), with an LCD display and with mass 0.2 kg, whereas our present HMD (n-vision) has a CRT display and mass 1.9 kg. This makes it likely that mass rather than smear causes the slower head motion. This is further indicated by De Vries and Padmos (1998), who compared the i-glasses HMD and the n-vision HMD, and found that with the heavier n-vision HMD head motion was consider ably slower than may be attributed to the larger instantaneous field of the latter compared with the i-glasses HMD. A further indication that a heavy HMD is unfavorable is that some subjects commented on the heaviness of the HMD.

Parallel to the above mentioned suppression of head motion in the HMD conditions during turning left, is the worse performance with HMD for TURNPOS, the lateral position error immediately after turning left (Figure 6). This suggests that the less head motion caused the worse performance in this condition.

For driving straight, the worse performance with HMD compared to the non-HMD conditions is not likely to be caused by suppressed head motion. Rather this may be caused by the less quality of the vehicle references in wearing a HMD. Additionally, the wiggling image caused by the image delay of 190 ms with respect to head motion is likely to be a detrimental factor in wearing a HMD as it hinders a stable perception of the car's position and orientation. The frequent subjects' reports of sickness or dizziness after HMD conditions may have to do with the wiggling image. This emphasizes the importance of technical developments that may decrease the latency between head motion and image motion. Increasing the speed of the image generator is among the most promising developments in this respect.

Given the few complaints of headache and the absence of complaints of eyestrain, it is improbable that deficient HMD optics, potentially giving problems with ocular accommodation and/or convergence (Mon-Williams and Wann, 1998), is responsible for its lower subjective and objective performance.

Effects of Head Mounted Mask and Head Slaved Windows vs. Full Screen. As said before, quantitative results differed only incidentally among the display conditions without HMD. For left turns, VIEWSPEED was larger with Head Mounted Mask than with the two Head Slaved Window conditions. This confirms Van Erp and Kappé (1997), who found for curve taking hardly any performance difference between Head Slaved Window Continuous (40 × 40°) and Full Screen (156° H × 42° V). However, Kappé (1997) and Kappé et al. (1997) found worse straight driving performance with a Head Slaved Window Continuous (50 × 50°) than with Full Screen (150° H × 50° V), which contrasts our results. It may be concluded that a Head Slaved Window of the present size, with a preference for continuous slaving, is a good alternative for Full Screen.

Effects of vehicle references with HMD. Generally, the three HMD conditions do not give different results. However, two findings indicate that for straight road driving HMD With References Generated is more favorable than HMD With See-through References: For the wider road segments LANEMEAN is significantly larger in the condition HMD. With See-through References than in HMD With References Generated; the largest HEADSD is obtained with HMD Without References and the smallest HEADSD is with HMD With References Generated.

Learning effects. The fact that the independent variable replica had only minor or no effects, indicates that there was no important general learning effect after the training trials. It is possible that this is caused by the absence of performance feedback after the first replica. The Absence Of Important Interactions Replica × Display Condition Indicates That The Effects Found Of Display Condition Did Not Disappear In The Last Replica. However, Some Smaller Interactions Replica × Display Condition (Not Shown) Suggest That Negative Effects Of Hmd Eventually May Become Less After Adequate Training Of Subjects.

CONCLUSIONS

The main conclusions are summarized as follows:

- Wearing an HMD was found to have negative effects on driving performance
- The restricted instantaneous field of view is not the cause of the decreased performance with HMD's. On the contrary, a field restriction may make subjects less vulnerable for simulator sickness.
- The large mass of the HMD and the considerable image delay are probably the factors responsible for its lower performance. Its is recommended to strive in further experiments to a low-mass HMD and faster image generation / low latency headtracking.
- Head slaved window of the present size (39°h), with a preference for continuous slaving, is a good alternative for full screen image presentation.
- When using an HMD for driving simulation it is recommended to apply vehicle references in the virtual environment.

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