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TNO Human Factors
Research Institute

Kampweg 5
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Phone +31 346 35 62 11
Fax +31 346 35 39 77

title

Effects of head-slaved and peripheral displays on lane-keeping performance and spatial orientation

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authors
B. Kappé
J.E. Korteling
J.B.F. van Erp

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auteurs:	Dr. B. Kappé, dr. J.E. Korteling, drs. J.B.F. van Erp
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Bij de Koninklijke Landmacht bestaat in toenemende mate behoefte aan advies met betrekking tot de vraag welke visuele informatie en op wat voor manier deze in voertuigsimulatoren moet worden aangeboden om de rijtaak goed uit te kunnen voeren. Met deze kennis is men in staat alleen de minimaal noodzakelijke beeldinformatie op een zo efficiënt mogelijke manier aan te bieden. Hierdoor wordt aanzienlijk bespaard op de kosten van het computer gegenereerde beeld (CGI) terwijl er tevens effectief kan worden getraind. In dit verband wordt in opdracht van het OC Rijden in het kader van het project 'Visuele informatie in voertuigsimulatoren' experimenteel onderzoek verricht naar mogelijkheden om kritische visuele informatie zo effectief en efficiënt mogelijk te presenteren.

Beelden die worden gepresenteerd in low-cost simulatoren en in bedieningsconsoles van op afstand bestuurde voertuigen geven veelal niet voldoende informatie voor een goede besturing en ruimtelijke oriëntatie. De effectiviteit van deze displays kan worden verbeterd door de *virtuele* kijkrichting hoofd-gestuurd te maken en/of door het beeld te omringen met een schematisch perifeer beeld. Het onderhavige rapport doet verslag van drie simulator experimenten waarin de effecten hiervan worden onderzocht op stuurprestatie en ruimtelijke oriëntatie. In Experiment 1 gaven voertuigreferenties of een hoofd-gestuurd display informatie over de virtuele kijkrichting. Voertuigreferenties verbeterden de voertuig besturing bij een standaard 50°×50° display. Het hoofd-gestuurde display van dezelfde grootte verbeterde de stuurprestatie nog meer, maar nog niet zodanig dat het niveau van een breed display (150°×50°) werd gehaald. In Experiment 2 en 3 werden effecten onderzocht van een geschematiseerde omgeving rond een hoofd-gestuurd display (50°×50°) en van het discreet of continu meebewegen van een hoofd-gestuurd display. Bij toevoeging van het geschematiseerde perifere beeld rond een hoofd-gestuurd display bleken voertuigbesturing (Exp. 2) en ruimtelijke oriëntatie (Exp. 3) vergelijkbaar met de prestatie met een breed, volledig gedetailleerd display. De prestatie met het discrete hoofd-gestuurde display was beter dan met het continu bewegende display. Deze resultaten laten zien dat low-cost voertuigsimulatoren (en ook interfaces voor onbemande platforms) uitgerust kunnen zijn met een relatief bescheiden display dat even effectief is als een traditioneel meerkanaals display.

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TNO Human Factors Research Institute
Soesterberg, The Netherlands

Effects of head-slaved and peripheral displays on lane-keeping performance and spatial orientation

B. Kappé, J.E. Korteling, J.B.F. van Erp

SUMMARY

The images presented in low-cost vehicle simulators and in operator interfaces of Remotely Piloted Vehicles (RPVs) often do not provide enough information for optimal vehicle control and do not elicit sufficient spatial orientation. To improve the effectiveness of these images, the *virtual* viewing direction can be 'head-slaved', or the display can be surrounded with a less detailed peripheral image. Three simulator experiments were used to evaluate the effect of these techniques on steering performance and spatial orientation. In Experiment 1, vehicle references or a head-slaved display provided feedback on the virtual viewing direction. Vehicle references brought about some improvement in lane-keeping performance when a standard 50°×50° (h×v) display was used. A head-slaved display (50°×50°) allowed better steering performance, but not up to the levels obtained with a traditional three-channel display (150°×50°). Experiments 2 and 3 addressed the effects of surrounding the head-slaved display with a less detailed peripheral image, and of moving the head-slaved display discretely or continuously. With the peripheral image (surrounding a head-slaved display), lane-keeping performance (Experiment 2) and spatial orientation (Experiment 3) were just as good as they were with a traditional three-channel display. Performance with the discretely moving head-slaved display was superior to the performance with the more sophisticated continuously moving display. The results show that low-cost simulators and RPV operator interfaces can be equipped with an efficient low-cost display that is just as effective as a normal multi-channel display.

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Soesterberg

Effecten van hoofd-gestuurde en perifere displays op stuurprestatie en ruimtelijke oriëntatie

B. Kappé, J.E. Korteling, J.B.F. van Erp

SAMENVATTING

Beelden die worden gepresenteerd in low-cost simulatoren en in bedieningsconsoles van op afstand bestuurde voertuigen geven veelal niet voldoende informatie voor een goede besturing en ruimtelijke oriëntatie. De effectiviteit van deze displays kan worden verbeterd door de *virtuele* kijkrichting hoofd-gestuurd te maken en/of door het beeld te omringen met een schematisch perifeer beeld. Het onderhavige rapport doet verslag van drie simulator experimenten waarin de effecten hiervan worden onderzocht op stuurprestatie en ruimtelijke oriëntatie. In Experiment 1 gaven voertuigreferenties of een hoofd-gestuurd display informatie over de virtuele kijkrichting. Voertuigreferenties verbeterden de voertuig besturing bij een standaard 50°×50° (h×v) display. Het hoofd-gestuurde display van dezelfde grootte verbeterde de stuurprestatie nog meer, maar nog niet zodanig dat het niveau van een breed display (150°×50°) werd gehaald. In Experiment 2 en 3 werden effecten geëvalueerd van een geschematiseerde omgeving rond een hoofd-gestuurd display (50°×50°) en van het discreet of continu meebewegen van een hoofd-gestuurd display. Bij toevoeging van het geschematiseerde perifere beeld rond een hoofd-gestuurd display bleken voertuigbesturing (Exp. 2) en ruimtelijke oriëntatie (Exp. 3) vergelijkbaar met de prestatie met een breed, volledig gedetailleerd display. De prestatie met het discrete hoofd-gestuurde display bleek beter dan met het continu bewegende display. Deze resultaten laten zien dat low-cost voertuigsimulatoren (en ook interfaces voor onbemande platforms) uitgerust kunnen zijn met een relatief bescheiden display dat even effectief is als een traditioneel meerkanaals display.

1 GENERAL INTRODUCTION

There are situations in which only a limited amount of visual information can be presented. In low-cost vehicle simulators and in video games, the image generator does not allow a high resolution image to be presented for a wide field of view. However, if traffic signs are to be legible and perception of oncoming traffic is to be adequate, a high resolution image is required. If sharp curves and intersections are to be negotiated, a wide field of view is needed as well. There are similar problems with the interface of a Remotely Piloted Vehicle (RPV) , since the capacity of the datalink that transmits video images may not be sufficient to produce high-resolution video with an adequate field of view and update rate. The present study investigated methods for optimizing the effectiveness of a display.

The visual system faces a similar problem in the perception of visual information. It too needs to optimize the sampling of visual information. The visual system can increase its effectiveness in two ways. First, the viewing direction of the eye can be changed to widen the *field of regard* (i.e., the part of the environment that can be observed by changing the viewing direction). Second, by varying the resolution of the eye across the field of view (high resolution in the fovea, lower resolution towards the periphery) the visual system can—for a fixed dataflow—sample with a higher resolution and/or for a wider field of view.

By capitalizing on the above mentioned properties of the visual system, it is possible to improve display effectiveness in simulators and in RPVs. The field of regard of a display may be increased by changing the *virtual* viewing direction, i.e. the viewing direction for which the Computer Generated Image (CGI) is generated or for which the RPV camera registers the remote environment. Also, the available visual information can be distributed more economically by reducing the level of detail and/or resolution of images presented in the peripheral field of view. A detailed display presented in the viewing direction surrounded by less detailed visual information in the periphery may be just as effective as a traditional three-channel display with a uniform level of detail. In the present study, three experiments were conducted to evaluate the effect of these two techniques on lane-keeping performance (Experiments 1 and 2) and on spatial orientation (Experiment 3).

2 EXPERIMENT 1: CONTROLLING THE VIRTUAL VIEWING DIRECTION

2.1 Introduction

In a vehicle simulator, or in an RPV operator interface, a display presents part of a *virtual* environment, i.e. a computer generated or remote environment. Which part of the virtual environment is presented depends on the virtual viewing direction and the size of the instantaneous field of view.

Traditionally, the virtual viewing direction is coupled to the simulated or remote vehicle, and is generally aimed in the direction of travel. Obviously, this narrows the operator's field of regard, since a change in virtual viewing direction can only be brought about by a change in orientation of the vehicle. Correctly negotiating an intersection with a narrow field of view is thus almost impossible. Self control of the virtual viewing direction with respect to the vehicle may be a better option. This allows the virtual environment to be observed in any direction, without changing the orientation of the vehicle. In Experiment 1, the latter method of controlling the virtual viewing direction is studied.

Controlling the virtual viewing direction, e.g. by rotation of the head, may be an efficient method to increase the field of regard, but the perceptual consequences may be severe. Experiments on RPVs equipped with 'pan-and-tilt' cameras, that presented the camera images on a monitor, revealed poor vehicle control (Holzhausen, 1991; Miller & McGovern, 1988; McGovern, 1987, 1988, 1991; Mestre, Peruch, Terre & Fournier, in press) and loss of spatial orientation (Carver, 1987, 1988; Van Breda & Passenier, 1993). Subjects have difficulty in assessing the viewing direction with respect to the vehicle and in discriminating changes in viewing direction and changes in orientation of the vehicle. Obviously, this will hamper adequate vehicle control and does not permit the development of a sense of spatial orientation.

There are two ways to decrease these adverse effects of controlling the virtual viewing direction on vehicle control and spatial orientation. The first way is to present additional visual information on the virtual viewing direction. Vehicle references, for instance, allow the virtual viewing direction to be inferred from the part of the vehicle currently in sight. This also allows the observer to distinguish between vehicle rotation and changes in virtual viewing direction, since the latter change the part of the vehicle currently in sight, whereas the former does not. The second way is to introduce extra-retinal information by presenting the images in the correct viewing direction. This presentation method is commonly utilized in *virtual reality* setups, which present head-slaved images on a head-mounted display. Several authors have investigated vehicle control using a head-slaved camera in combination with a head-mounted display (McGovern, 1988; Pepper, 1986; Spain, 1988, 1991; Umeda, Martin & Merrit, 1991; De Vries & Padmos, 1997). The results show that head-mounted displays permit proper vehicle control and adequate spatial orientation (Henry & Furness, 1993), although performance is not as good as with direct view, probably because of the limited instantaneous field of view, the lower resolution and the time lag between head- and camera- movements (Grunwald & Kohn, 1994).

Until now, the effects of visual and extra-retinal information on steering performance with a controlled virtual viewing direction have not been compared. Therefore, Experiment 1 addressed the effects of these two principles on steering performance while head-slaved images (yaw movements only) are presented. Vehicle references provided visual information about the virtual viewing direction, and a head-slaved display provided extra-retinal information. To force changes in viewing direction, subjects had to track a fixation pole positioned at some distance to the road. This task was supposed to mimic the changes in viewing direction which normally occur when a driver approaches an intersection. A wide field of view (150°×50°, h×v) was presented as a control condition.

The head-slaved display utilized in Experiment 1 consisted of three adjacent displays, constituting a field of regard of 150°×50°. On these displays a 50°×50° image was presented in the virtual viewing direction. In theory, such a head-slaved display may be generated by a single channel CGI or camera image which is positioned in the viewing direction using a head-tracker and special video hardware. Similar to a head-mounted display a head-slaved display presents head-slaved images in the viewing direction, and allows different parts of the virtual environment to be regarded as the observer turns his head. However, compared with a head-mounted display, a head-slaved display does not suffer as much from delay between changes in the real and virtual viewing direction. With an head-mounted display, this delay causes the parts of the virtual environment that were observed in the old viewing direction to be briefly presented in the new viewing direction. This results in a percept of an unstable virtual world, dizziness, and simulator sickness. With a head-slaved display, however, such a delay merely causes the head-slaved display to arrive a little late in the new viewing direction. The parts of the virtual environment presented by the head-slaved display will always remain at their correct position, resulting in a stable virtual environment. Compared with a head-mounted display, a head-slaved display may improve lane-keeping performance and spatial orientation, and reduce dizziness and simulator sickness.

2.2 Method

Subjects. Twelve college-educated, right-handed, male subjects (mean age 22.3 y, sd 2.0 y) were recruited from the TNO subject pool. All subjects had normal or corrected to normal vision, were paid for their participation, and had no experience with similar operator tasks.

Task. Subjects had to steer a simulated vehicle along a narrow straight lane by means of a joystick, while correcting for a side-wind. Subjects were instructed to do their best to keep to the center of the lane. In order to force subjects to make head movements, subjects had to 'point the nose' towards fixation poles, and keep the pole centered in the display. To make sure that subjects were attending to the poles the poles could suddenly change color, whereupon subjects had to press a response foot pedal.

Apparatus. All images were generated by a three-channel Evans & Sutherland ESIG 2000 image generator (30 Hz update rate), and projected by a Seos PRODAS HiView S-600 projection system, consisting of a spherical dome and three video projectors (radius 3.4 m, 150°×50°, 2400×600 pixels (H×V), 60 Hz, non-interlaced). The subject's head was positioned in the center of the projection. head orientation was registered by a Polhemus Fast-track head-tracker (resolution 0.15°, 30 Hz). During the experiment, subjects wore a plastic helmet which carried the sensor coil. The total delay of the head-tracker image-generator display loop was about 60 ms. The head-slaved display was simulated by a head-slaved box surrounding the viewpoint, which had a 50°×50° window that allowed a view of the virtual environment. Additional PCs were used to run the vehicle model (30 Hz), collect head-tracker data (30 Hz) and store data (10 Hz). The subject was seated in a chair with one right armrest, in which a spring loaded joystick was mounted (full deflection -25°/+25°, 0.4 N). A response switch was positioned near the subject's right foot. The simulated vehicle moved at a constant speed of 25 m/s. Its turn rate was proportional to sideward joystick deflection, and was modeled with a first-order filter with a time constant of 0.42 s. Full deflection resulted in a maximum heading rate of 12.5 °/s. A side-wind was modeled as a random input to a first order filter with a time constant of 4.2 s, superimposed upon the joystick signal. The side-wind alone could result in a maximum heading rate of +/- 1 °/s.

Image. The CGI presented a straight 3.6 m wide lane, with 0.15 m wide delineators. The lane and surrounding surfaces were textured with coarse and fine textures (visible up to 50 and 20 m in front of the vehicle, respectively). In a 1 × 5 km area surrounding the lane, rectangular elements were positioned randomly on adjacent 25×25 m plots. The elements were brightly colored and had a high-contrast coarse texture (see Figure 1). The elements were 3 × 3 m or 6 × 6 m, and their height (0.5 to 32 m) varied with distance from the lane.

The size of the fixation poles that were positioned in the environment were 1.5 m × 0.25 m and their color could alternate between dark red and dark blue. Only one pole was visible at a time. A pole appeared when the vehicle was at a longitudinal distance of 200 m, and disappeared when the vehicle was at 25 m. The poles could change color at an unpredictable moment (0 to 3 times per pole). The position of each of the 20 poles (-12, -6, 6 or 12 m from the lane, 5 poles for each position) varied randomly according to one of six scenarios.

Variables and statistical design. Two independent variables were manipulated: vehicle references and display type. Vehicle references could be introduced by simulating a compact sedan, observed from the driver's normal viewpoint, see Figure 1. Three display types were used which allowed the subjects to change the virtual viewing direction over 150°, i.e., the displays had the same field of regard (150°×50°). However, the displays differed in the presentation of the direction in which the images were presented (fixed or head-slaved) and in the size of the instantaneous field of view (50° vs 150°).

This resulted in a fixed *standard display* (50°×50°) positioned in front of the observer presenting a head-slaved image on a fixed position, a real *head-slaved display* (50°×50°) presenting environment images in the viewing direction, and a traditional three-channel *wide display* (150° × 50°) in which the entire three-channel display presented a wide virtual environment. Figure 1 shows these three display types. In Figure 1c the vehicle references seem a little awkward and distorted because the photographs are not made from the (correct) viewpoint of the subject.

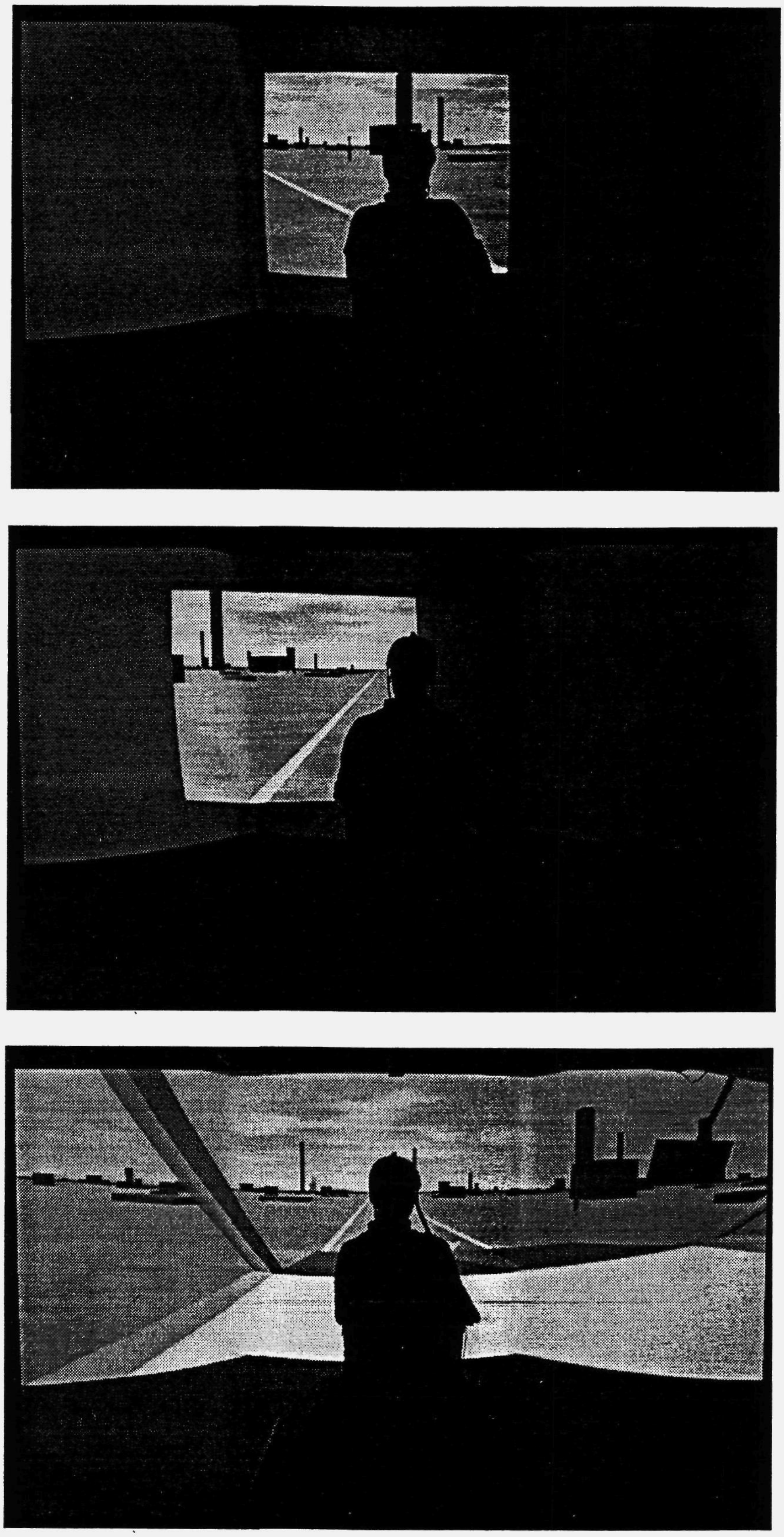

Fig. 1 The different display types used in experiment 1: a) the fixed standard display without vehicle references (note that the subject looks to the right side), b) the head-slaved display without vehicle references, and c) the wide display with the large field of view including vehicle references.

The two independent variables were manipulated in a full factorial within subjects design. In each block, subjects were presented with all six conditions order-balanced between subjects by means of a Latin square (Wagenaar, 1969), with six pole-position scenarios order-balanced between blocks.

Five dependent variables were determined: standard deviation (sd) of lateral position (m), sd lateral speed (m/s), sd heading rate (°/s), mean absolute viewing error (°), and percentage of correct responses to color changes. The first three variables characterize lane-keeping performance, the last two characterize the subject's viewing performance. The standard deviations were calculated over each 180 s run. The mean absolute viewing error (heading error only) was calculated from the viewing error with respect to the fixation pole, during the intervals when a pole was visible.

The dependent variables were checked individually for outliers. Scores that deviated by more than 3 SD from the overall mean were marked missing and were excluded from the analysis. Then, a 3 (display condition) × 2 (vehicle reference) × 2 (repetition) ANOVA was conducted.

Procedures. Subjects participated in pairs. First, subjects received a brief written explanation about the general nature and procedures of the experiment. The instructor then showed the projection dome, chair, joystick and helmet, and explained the purpose and task in more detail. Subsequent training consisted of two blocks of five conditions: the first in fixed order, the second order-balanced between subjects. In each of the two experimental blocks (lasting 20 min.) The subjects performed all 6 conditions (3 min. each), in a between-subjects balanced order. During the short transition periods between trials, the subjects were informed about the nature of the subsequent *condition.* The two subjects worked in pairs: each subject completed a block while the other subject rested in a waiting room.

2.3 Results

The three dependent variables reflecting lane-keeping performance showed a similar main effect of display type: lateral distance, $F(2,20)=41.89$, $p<.001$, lateral speed, $F(2,22)=60.76$, $p<.001$ and heading rate, $F(2,20)=23.56$, $p<.001$, were found to have the highest standard deviation with a standard display, a lower standard deviation with the head-slaved display, and the lowest standard deviation with the wide display, see Figure 2. Three post-hoc Tukey tests indicated that the standard deviations all differed significantly.

Vehicle references had a main effect on sd lateral speed, $F(1,11)=9.5$, $p<.05$: when the references were present, sd lateral speed was reduced. However, a post-hoc Tukey test on the interaction of vehicle references with display type, $F(2,22)=8.47$, $p<.01$, indicated that vehicle references only reduced sd lateral speed with a standard display, see Figure 2. A similar interaction was found for sd lateral position, $F(2,20)=8.05$, $p<.01$: a post-hoc Tukey test indicated that vehicle references only reduced sd lateral position with a standard display.

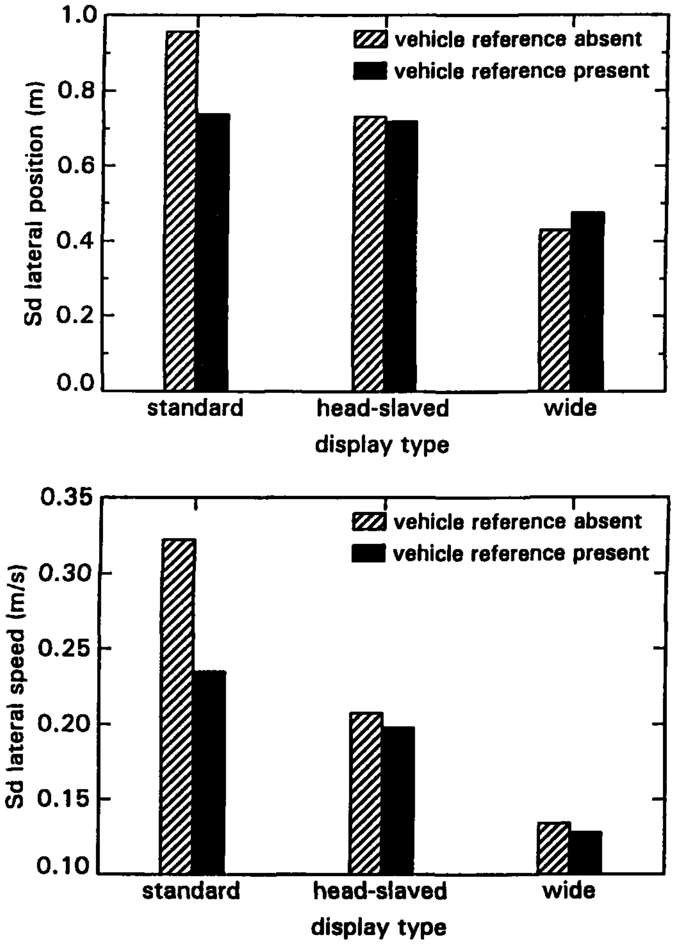

Fig. 2 The effect of display type and vehicle references on sd lateral position and sd lateral speed. Vehicle control is poorest with the standard display, and best with the wide display. Vehicle references reduce sd lateral position and sd lateral speed, but only with a standard display.

The viewing error was affected only by display type, $F(2,20)=35.75$, $p<.001$: viewing error was largest with the standard display, less for the wide display, and smallest with the head-slaved display, as shown in Figure 3. A post-hoc Tukey test indicated that the viewing error for the three display types differed significantly from each other. The percentage of correct responses to color changes of the pole, about 90% on average, did not show any effect of the independent variables, indicating that the subject's attention to the poles did not vary across conditions. The analyses did not show any interactions.

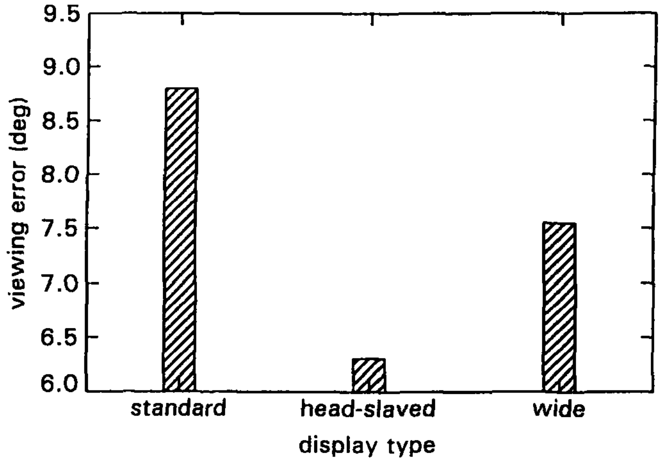

Fig. 3 The effect of display type on viewing error. The error is largest with the standard display, and smallest with a head-slaved display.

2.4 Discussion

The virtual viewing direction, i.e. the direction of the camera image or the CGI with respect to the simulated or remote vehicle, can be changed to increase the field of regard and thus improve the effectiveness of a display with a limited instantaneous field of view. Previous research has shown that steering performance is generally poor when such images are presented on a fixed standard monitor, presumably due to the absence of visual and/or extra-retinal information about the virtual viewing direction. Experiment 1 evaluated two methods for improving steering performance with such head-slaved images. First, vehicle references were presented which provided visual information on the virtual viewing direction. Second, a head-slaved display was used, which provided extra-retinal information on the virtual viewing direction.

The results of Experiment 1 confirm that vehicle control is poor when head-slaved images are presented on a fixed standard display: sd lateral position, sd lateral speed and sd heading rate doubled in comparison with the wide display. The introduction of visual information concerning the virtual viewing direction improved performance somewhat: vehicle references reduced sd lateral position and sd lateral speed. The effect of extra-retinal information on the virtual viewing direction was more pronounced. Not only did the head-slaved display reduce sd lateral position and sd lateral speed, it also reduced sd heading rate. Although these results suggest that visual and extra-retinal information are about equally effective in improving vehicle control, the viewing error with vehicle references was much larger than with a head-slaved display. A large viewing error allowed a larger portion of the delineators to be visible because this error probably results from looking more in the direction of the road ahead. This may have facilitated control, since it has been shown that delineators provide the most critical visual information in lane-keeping (Riemersma, 1981, 1982, 1987; Beusmans, 1995; Beall &

Loomis, 1996). When the much smaller viewing error is taken into account, the effect of the head-slaved display is more robust than the effect of vehicle references.

Many subjects reported spontaneously on the large perceptual differences between the standard display and the head-slaved display. With the former, a change in the virtual viewing direction 'rotated' the virtual environment, which made the subjects feel slightly uncomfortable. The latter allowed subjects to perceive a stable virtual environment, in which a change in viewing direction merely revealed a different part of the virtual environment. Introduction of vehicle references only decreased this effect with regard to lateral speed and position and with a standard display. According to the subject reports, when the virtual viewing direction was changed in a virtual environment, the vehicle seemed to swing to and fro when observed on a standard display with vehicle references, whereas a head-slaved display allowed perception of a normal, stationary vehicle. These effects suggest that, under the present conditions, extra-retinal information about the virtual viewing direction is of primary importance in the interaction with the (virtual) environment, because it generates the percept of a stable environment. Providing *visual information* on the virtual viewing direction by presenting vehicle references was not sufficient for producing a stable visual world in which head rotations and vehicle rotations could be well-discriminated.

In summary: both visual and extra-retinal information on the virtual viewing direction may improve steering performance with head-slaved images. However, providing extra-retinal information using a head-slaved display resulted in superior vehicle control and perception of a stable environment. Nevertheless, the head-slaved display did not lead to the performance levels obtained with a wide display. This indicates that in the present task, the $50° \times 50°$ field of view decreased lane-keeping performance even when viewing direction could be changed. A larger field of view is therefore required for optimal steering performance. In low-cost simulators, however, the traditional multi-channel CGI systems are often not feasible. A more parsimonious solution might be to surround a rich head-slaved display with a less detailed image. Such a display, which is tailored to the properties of the visual system, may be just as effective as a traditional display that provides a uniform level of detail throughout the field of view. In Experiments 2 and 3 this option was evaluated in a steering task and a spatial orientation task, respectively.

3 EXPERIMENTS 2 AND 3: PERIPHERAL DISPLAYS

3.1 Introduction

Apart from presenting head-slaved images on a head-slaved display a second way to improve display effectiveness is to distribute the available visual information efficiently. Visual resolution decreases rapidly with increasing eccentricity, and it seems logical to distribute the visual information on a display accordingly. In the literature on visual perception, two psychological modalities are often discriminated: the *focal* and the *ambient* modality (e.g., Leibowitz & Post, 1982; Leibowitz, 1988). The focal modality is concerned with discrimination and identification of stimuli, i.e. the 'what' question, and is optimal in the central visual field. The ambient modality is concerned with stimulus detection, spatial orientation, (ego) motion perception, i.e., the 'where' question, and guides the fovea towards conspicuous details that require further inspection. Restricting the field of view decreases the information available to the ambient modality. The effects of such a restriction on driving performance are in line with the theory: a decreased performance in detecting road signs, avoiding obstacles and manoeuvring in a confined space (Cavallo & Laurent, 1988; Pepper, 1986; Spain, 1988, 1991; Wood & Troutbeck, 1992, 1994).

Notwithstanding its relevance in stimulus detection, spatial orientation, and (self)motion perception, only little visual information is needed for adequate stimulation of the ambient modality. Detection of peripheral stimuli merely requires sufficient contrast and vigilance. Spatial orientation can be improved with simple peripheral stimuli. The spatial orientation of RPV camera operators, for instance, is substantially improved if the camera display is surrounded by view of a simple *Computer Generated Grid* (Kappé, Van Erp & Korteling, 1997). Perception of the direction of ego-motion does not require much visual information. Several experiments have shown that perception of heading over a random-dot ground plane is virtually independent of the number of dots depicted. For instance, Warren, Morris and Kalish (1988) found that the just noticeable difference of heading direction only increased when the number of dots dropped below 10 (for a field of view of $40° \times 30°$ h$\times$v). Similarly, when driving a car, delineators provide all the information required in lane-keeping (Riemersma, 1981, 1982, 1987; Beall & Loomis, 1996; Beusmans, 1995; Land & Horwood 1995), again indicating that tasks based on the ambient visual modality do not require complex visual information.

In the light of the modest information that is needed for proper stimulation of the ambient visual modality, the effectiveness of a head-slaved display with a limited instantaneous field of view can be improved by introducing a less detailed image in the periphery. Using the display system of Experiment 1, the head-slaved display can be surrounded by a simple peripheral image presented on the remainder of the wide three-channel display. One of the drawbacks of the head-slaved display presented in Experiment 1, however, is that special video hardware is required to continuously change the position of the head-slaved display on the displays. A simpler method is to change the position of the head-slaved display discretely, i.e. by jumping from one display channel to another when the observer's viewing direction crosses their border. The type of head-slaved display movement is not expected to be critical, since both continuous and discrete head-slaved displays present the images in the correct viewing direction.

Experiments 2 and 3 evaluated the effects of a simple peripheral image, surrounding a detailed head-slaved display, and compared its performance with a traditional three-channel display. The effects of moving the head-slaved display continuously or discretely were also evaluated, since the latter allows simpler hardware to be used for moving the head-slaved display over the display channels. In Experiment 2 a steering task was performed, similar to Experiment 1. Experiment 3 determined the effects of these two variables on spatial orientation by means of a spatial localization task. For both experiments (2 + 3) it was expected that the introduction of a sparse peripheral image would improve performance with the head-slaved display so that it is just as good as a traditional wide three-channel display.

3.2 Experiment 2: effects on lane-keeping performance

3.2.1 Method

Subjects. Ten college-educated, right-handed male subjects (mean age 22.0 y, sd 3.5 y) were recruited from the TNO subject pool. All subjects had normal or corrected to normal vision, were paid for their participation, and had no experience with similar operator tasks.

Apparatus. The experimental setup was identical to Experiment 1, except from a new Logitech Wingman joystick that was mounted on the armrest.

Task. Subjects had to steer a vehicle along a narrow straight lane by means of a joystick while correcting for a side-wind disturbance, and were instructed to do their best to keep to the center of the lane. Also, subjects had to point a head-slaved cursor at the bottom of a fixation pole positioned at some distance from the lane. The speed of the vehicle was set at 20 m/s.

Display. The virtual environment presented by CGI was almost identical to the virtual environment used in Experiment 1, with the exception that the rectangular elements in two 30 m wide zones next to the lane were removed and replaced by 1×1 m square tiles. The tiles were positioned on both sides of the lane at 3, 6, 12 and 30 m lateral distance at a longitudinal interval of 5 m. When viewed with the head-slaved display, tiles and edge lines stretched ad infinitum, and texture, rectangular elements and fixation pole were visible. The head-slaved cursor was a $2°\times2°$ plus sign. The peripheral image showed only edge lines and tiles up to 100 m in front of the vehicle, and a horizon.

Variables and statistical design. Two independent variables were manipulated: display type and movement type. Three display types (two plus a control condition) were used; *a head-slaved display* presenting a detailed image with a limited instantaneous field of view ($50°\times50°$) in the viewing direction (see Figure 1b), *a head-slaved display with a peripheral image* (shown in Figure 4), which depicted a less detailed image on the remainder of the $150°\times50°$ display. A traditional three-channel *wide display* was used as a control condition, and presented a detailed image on the entire three-channel display ($150°\times50°$) (see Figure 1c). Head-slaved display movement type determined how the image of the head-slaved display followed changes in the viewing direction (heading changes only): *continuously;* the image followed viewing direction smoothly, and *discretely;* only images belonging to three viewing directions were presented, these images were presented stepwise on only one of the three 50°x 50° display channels at a time located in the correct direction relative to the position of the head.

Fig. 4 The head-slaved display surrounded by a simple peripheral image.

The two independent variables were manipulated in a 2 (head-slaved display type)×2 (head-slaved display movement) within-subjects design with the traditional three-channel display used as a control condition. In each block, subjects drove all five conditions semi-order balanced between-subjects by means of a 6×6 Latin square.

Four dependent variables were determined: sd lateral position (m), sd lateral speed (m/s), sd heading rate (°/s), and mean absolute viewing error (°). The mean absolute viewing error was defined as the average absolute angle (the square root of the squared heading and pitch errors) between the head-slaved cursor and the base of the fixation poles calculated over the interval when the poles were visible.

The data were checked individually for outliers. Scores that deviated by more than 3 sd from the overall mean were marked missing and excluded from analysis. The results were analyzed with a 2 (head-slaved display type)×2 (head-slaved display movement) ANOVA, with the three-channel display as a control condition and three repetitions per cell.

Procedures. First, subjects received a brief written explanation concerning the general nature and procedures of the experiment. The instructor then showed the projection dome, chair, joystick and helmet, and explained the purpose and the task in more detail. Subsequent training consisted of two blocks of five conditions each: the first in fixed order, the second order balanced between subjects. In each of the three experimental blocks (taking about 17 min. each), subjects performed 5 order-balanced trials (3 min. each), representing the 5 experimental conditions. The subjects were informed about the nature of the following condition. Subjects operated in pairs: each subject completed a block while the other subject rested in a waiting room.

3.2.2 Results

The head-slaved display type had a main effect on sd lateral position, $F(1,9)=29.31, p<.001$, and sd lateral speed, $F(1,9)=9.85, p<.05$: lane-keeping was more accurate when a simple peripheral image surrounded the detailed head-slaved display, see Figure 5. A planned comparison of the two head-slaved display types with the thee-channel display indicated that performance with the peripheral image was similar to the performance with the three-channel display.

Head-slaved display movement had an effect on two dependent measures: sd lateral position, $F(1,9)=9.71, p<.05$, and sd lateral speed, $F(1,9)=8.78, p<.05$, were lower when the head-slaved display moved *discretely*. A similar effect of head-slaved display movement on sd heading rate, $F(1,8)=5.05, p=.051$, almost reached significance.

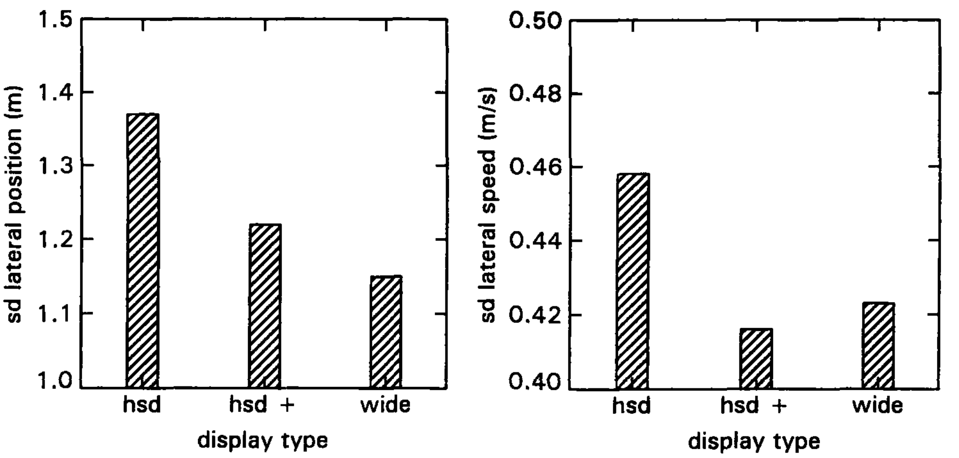

Fig. 5 The effect of display type on sd lateral position and sd lateral speed. When a sparse peripheral image surrounded the head-slaved display (hsd +), steering performance became similar to the performance with the three channel display used as a control condition.

The ANOVA on the viewing error data only indicated a main effect of head-slaved display movement, $F(1,9)=8.81$, $p<.05$: viewing error increased with a discretely moving display. There were no interactions.

3.2.3 Discussion

Display efficiency in low-cost vehicle simulators and in RPV operator interfaces can be increased if visual information is more economically distributed. This can be done by a head-slaved display presenting detailed information in the central visual field surrounded by less detailed information in the periphery. In this way the characteristics of the display reflect the properties of the human visual system. Such a system is more parsimonious than presenting the entire field of view of a display at a uniform level of detail. If the head-slaved display is to be presented exactly in the viewing direction, special video hardware is required, since parts of the head-slaved display may have to be presented simultaneously on two adjacent displays. A simpler method is to present a head-slaved display on one display channel at a time and switching it discretely from one channel to another.

The results of Experiment 2 show that lane-keeping performance based on a head-slaved display with a sparse peripheral image is just as good as lane-keeping performance with a wide three-channel view. The standard deviations of lateral position, lateral speed and heading rate with this type of display do not differ from the standard deviations found with the traditional three-channel display. Thus, the simple peripheral image used in the present experiment, depicting a horizon, delineators and a handful of tiles, appears to fulfill the requirements of the ambient visual modality in a lane-keeping task.

Lane-keeping performance with the discretely moving head-slaved display turned out to be better than with the continuously moving head-slaved display. This can be attributed to two factors. Firstly, a larger viewing error was observed with the discretely moving head-slaved display; since subjects tracked the poles less accurately they had a better view of the delineators. Improved driving performance can thus be attributed to improved visibility of the delineators, which provide the main visual information in lane-keeping. The second factor is that the edges of a discretely moving display do not generate any optic flow. The optic flow (Gibson, 1950, 1966) generated by the edges of a continuously moving head-slaved display resembles the optic flow generated by a vehicle rotation. This additional flow may have triggered some unintended steering actions.

In conclusion: lane-keeping performance with a head-slaved display surrounded by a sparse peripheral image is just as good as with a traditional three-channel display. Furthermore, a discretely moving head-slaved display allows better lane-keeping than a continuously moving display. However, as well as a function in the perception of ego-motion, the ambient visual modality also plays a role in spatial orientation. Therefore, the effects of peripheral images and of head-slaved display movement were also evaluated in a spatial orientation task.

3.3 Experiment 3: effects on spatial orientation

The ambient visual modality is not only relevant in the perception of ego-motion, but it also plays an important role in spatial orientation. By means of a spatial localization task we determined the effects of the introduction of sparse peripheral images on spatial orientation. Similar to Experiment 2, the effect of type of head-slaved display movement on spatial orientation was also investigated. Subjects had to pay attention to the position of two poles simultaneously, and aim a head-slaved cursor at their presumed location after the poles had disappeared.

3.3.1 Method

Subjects and task. Experiment 3 was conducted adjacent to Experiment 2, and involved the same 10 subjects and apparatus. The principal difference concerned the task that subjects had to perform. To test the subject's spatial orientation, two poles were presented simultaneously on the left- and right-hand side of the lane. At unpredictable moments, the poles disappeared, the vehicle stopped, and a wide field of view was presented. Then, subjects had to position a head-slaved cursor at the presumed location of the poles, and press a foot switch to denote its position. In addition to monitoring the poles, subjects had to steer the vehicle along a straight lane. The characteristics of the simulated vehicle and the side-wind disturbance were almost the same as in Experiment 2, although the speed was varied randomly and gradually between 4 and 6 m/s.

Display. Apart from the poles, the virtual environment was identical to Experiment 2. Two poles were visible at a time, positioned on the left- and right-hand side of the lane at a lateral distance of 30 m. The poles were always more than 50° apart, and could not be observed simultaneously with the head-slaved display. At the moment the poles disappeared their longitudinal position varied randomly between 10 and 35 m, and 35 and 60 m. The location of six pairs of poles had to be estimated each run, and the position of the nearest pole alternated between left and right. To prevent subjects from scanning the position of the poles just before they disappeared, the time during which the poles were visible was varied randomly between 8.3 and 12.5 s.

Variables and statistical design. Two independent variables were manipulated: display type and head-slaved display movement. Four display types (three plus a control condition) could be presented: *a head-slaved display,* presenting a 50°×50° (h×v) image in the viewing direction (see Figure 1b), *a head-slaved display with peripheral image,* the peripheral image being on the remaining sections of the 150°×display (see Figure 4), *a head-slaved display with peripheral image and poles,* which also showed the poles in the peripheral image. A *traditional three-channel display* was used as a control condition, and it presented a detailed image on the entire three-channel display (150°×50°). Head-slaved display movement type determined how the images of the head-slaved display followed changes in the viewing direction (heading changes only): *continuously;* the images followed viewing direction smoothly, and *discretely;* only images belonging to three viewing directions were presented, these images were presented stepwise on only one of the three 50°×50° display channels at a time located in the correct direction relative to the position of the head. In each 180 s run the subjects estimated the position of 6 pairs of poles. In each block, the subjects were presented with all seven conditions semi-order balanced between subjects by means of an 8×8 Latin square (Wagenaar, 1969), with one of 35 pole position scenarios per condition (randomly drawn from 35 different scenarios, without substitution).

Four dependent variables were determined: viewing error (°), sd lateral position (m), sd lateral speed (m/s), and sd heading rate (°/s). The viewing error is a measure for the accuracy of spatial orientation, and was defined as the absolute angle (the square root of the squared heading and pitch error) between the position of the head-slaved cursor and the base of the fixation pole, averaged over the twelve poles that were estimated each run.

The data were checked for outliers for each dependent variable separately. Scores that deviated by more than 3 SD from the overall mean were marked missing and excluded from the analysis. The results were analyzed in a 3 (Head-slaved display type)×2 (Head-slaved display movement) ANOVA with the traditional three-channel display as a control condition, and three repetitions per cell. In a planned comparison, the performance with the three head-slaved display types was compared with the performance with the traditional three-channel display.

Procedures. First, subjects received a brief written explanation concerning the general nature and procedures of the experiment. The instructor then explained the purpose and task in more detail. The subsequent training consisted of two complete blocks of seven order-balanced conditions. The instructor stressed that monitoring the poles was the primary task, but that lane-keeping was important as well. In each of the three experimental blocks (about 20 minutes) that followed, the subjects performed seven order-balanced trials (2,5 min.) representing the seven conditions. The subjects were informed about the nature of the subsequent condition and worked in pairs: each subject completed a block while the other subject rested in a separate waiting room.

3.3.2 Results

The expected effect of display type on viewing error appeared only as a trend, $F(2,18)=2.8$, $p=.087$; viewing error decreased when the peripheral information surrounding the head-slaved display increased. However, viewing error with the head-slaved display and the head-slaved display with a sparse peripheral image were significantly higher than with the three-channel control condition $F(1,149)=19.45$, $p<.0001$ and $F(1,149)=6.67$, $p<.05$). Viewing error with the head-slaved display with sparse peripheral image and poles was identical to the viewing error obtained with the traditional three-channel display. The type of head-slaved display movement had a main effect on viewing error, $F(1,9)=10.73$, $p<.01$: viewing error was smallest when the head-slaved display moved discretely.

Lane-keeping performance in Experiment 3 was similar to that in Experiment 2. The standard deviation of lateral position (trend only $F(2,18)=2.98$, $p=.076$), lateral speed, $F(2,18)=3.89$, $p<.05$, and heading rate $F(2,18)=5.31$, $p<.05$ all decreased with increasingly complex peripheral images. Again, the type of head-slaved display movement had an effect on lane-keeping performance: sd lateral position, $F(1,9)=6.60$, $p<.05$, sd lateral speed $F(1,9)=17.09$, $p<.01$ and sd heading rate $F(1,9)=8.83$, $p<.05$ were reduced when the head-slaved display moved discretely.

There were no significant interactions.

3.3.3 Discussion

The ambient modality plays not only a role in the perception of ego-motion, but also in spatial orientation. Adequate stimulation of the ambient modality requires a wide field of view and a modest level of detail. In vehicle simulators and in RPV operator interfaces, such a wide field of view is usually presented with a uniform level of detail or resolution. Such an arrangement wastes visual information because in the peripheral field of view, resolution is higher than necessary for the ambient modality. Therefore, a detailed head-slaved display surrounded by a sparse peripheral image may well prove to be just as efficient as a three-channel display at a uniform level of detail. In Experiment 3 the performance with such displays was evaluated and compared with the performance with a traditional three-channel display in a spatial orientation task.

The effect of the type of Head-slaved display indicates that spatial orientation improves when the ambient visual modality is stimulated with a sparse peripheral image, although the improvement appeared as a trend only (p=.087). This effect was substantiated by an additional 3 (Head-slaved display type)×2 (Head-slaved display movement) ANOVA, in which the three-channel display (used as an isolated control group) was omitted. Here the type of head-slaved display did have a main effect on viewing error, $F(2,16)=8.95$, $p<.01$, again pointing to decreased viewing error when more peripheral information was available. This is in line with expectations: the rapidly decreasing resolution in the peripheral part of the visual system suggests that proper stimulation of the ambient visual modality requires only a modest amount of visual information. When the poles were visible in the sparse peripheral image, performance was similar to a traditional three-channel display presenting an image with a uniform level of detail.

The reduced viewing error in the presence of peripheral information can be attributed to two factors. First, peripheral information provides a *spatial structure* which allows one better to monitor the position in the environment of one looking at the other pole on the opposite side of the lane. Second, peripheral information improves the perception of *ego-motion*, which allows the changing direction in which the poles are observed to be perceived more accurately.

A discretely moving head-slaved display had a positive effect on spatial orientation: viewing error was reduced compared to a continuously moving head-slaved display. A discretely moving head-slaved display has its display edges in a constant position in the operators optic array. These edges may have served as reference lines allowing the position of the poles to be tracked more accurately.

In conclusion: the results show that if the ambient visual modality is to be stimulated properly, the display should have a large field of view. However, this does not have to be a display with a uniform level of detail: spatial orientation with a head-slaved display with a sparse peripheral image was found to be just as good as with a traditional three-channel display. This result was not unexpected, since the functions of the ambient visual modality, e.g. spatial orientation and perception of (ego)-motion, do not require highly detailed images. As in Experiment 2, performance with the discretely moving head-slaved display was found to be superior to performance with the continuously moving head-slaved display.

4 GENERAL DISCUSSION

The poor quality of the images displayed in low-cost vehicle simulators, 3D video-games and RPV operator interfaces, does not permit adequate lane-keeping and spatial orientation. Due to the limited capacity of the image generator or of the data-link between RPV and operator interface, the required wide field of view cannot be presented with sufficient detail. In the present study, the effectiveness of such displays was increased by tailoring them to the properties of the human visual system. An efficient display was thus obtained, which permitted lane-keeping performance and spatial orientation at levels that were similar to the levels obtained with a three-channel display.

In the first experiment, the virtual viewing direction could be changed to allow a larger field of regard using a display with a restricted field of view. The results show that a virtual environment should be presented with the same spatial properties as a normal environment. Normally, a change in the viewing direction only changes the part of the environment that is observed, but the *position* of objects relative to the observer does not change. This seemingly trivial observation becomes very important when a head-slaved virtual environment is presented on a standard display (stationary). In this situation, head rotations will change the position of objects with respect to the observer. If a (rapid) change in the virtual viewing direction (steered by head rotations) is not accompanied by a similar change in the viewing direction of the observer (aimed at the fixed display), the position of virtual objects with respect to the observer will change. This leads to the perception of an unstable virtual environment, swinging to and fro when "looking around" making head movements. Obviously, this does not permit proper vehicle control, and it is likely to result in a loss of spatial orientation. If the changes in the virtual viewing direction match the changes in the observer's viewing direction a stable virtual environment is perceived, and steering performance is adequately supported by the input. This also explains that the effect of vehicle references on steering performance was less pronounced than the effect of head-slaved displays on steering performance. Even when vehicle references allowed the virtual viewing direction to be inferred from the part of the vehicle currently in sight, they did not eliminate the percept of an unstable virtual environment. Nevertheless, the addition of frames of reference provided by stationary displays may explain that a simple stepwise movement of the head-slaved display showing only one out of three virtual viewing directions in the correct position relative to the head, proved to be better than more sophisticated smooth and continuous movement according to the observers head rotations. In this case, the visual references provided by the stationary displays yielded more benefit than the extra information that could be gathered by continuous scanning in a stable virtual world.

The effectiveness of a display can also be improved by increasing the field of view. Proper stimulation of the ambient visual modality is required for adequate perception of (ego) motion, spatial orientation and for the detection of areas of interest that may require foveal inspection. These functions are essential in vehicle simulators, in RPV operator interfaces and in 3D computer games. Traditionally, a display with a large field of view is generated at a uniform resolution and level of detail. However, since visual resolution decreases rapidly towards the periphery of the visual system, display effectiveness can be improved by fitting the visual information that is available to the properties of the visual system.

By means of a head-slaved display presented on three adjacent displays, a detailed image can be presented in the viewing direction, surrounded by a sparse peripheral image on the remaining area of the monitors. The results of Experiments 2 and 3 show that a head-slaved display with a peripheral image may be just as effective as a traditional three-channel display. It can be argued that the difference between the head-slaved display and the peripheral image was rather small in the Experiments 2 and 3: in the 30 m wide zones adjacent to the lane, visual information in the head-slaved display and the peripheral image was almost identical. However, notwithstanding this small perceptual difference, the generation of the peripheral image required substantially less computer power than generating the entire display at the level of detail of the head-slaved display. Here, the purpose was simply to show that such an arrangement is feasible. We do not know the optimal distribution of visual information over the field of view in driving simulators or RPV operator interfaces. This is a topic for future investigations.

Clearly, peripheral displays had a positive effect on driving performance and spatial orientation, even though it presented relatively little information. A peripheral display presents information to the ambient visual modality, which improves (ego) motion perception and spatial orientation. In the present study, both the head-slaved display and the peripheral display presented the same virtual environment, albeit at a different level of detail. Sometimes, the peripheral display may present an even more rudimentary environment. In some RPVs only one camera image is available to the operator, due to the restricted capacity of the datalink. In such a case, peripheral information may be presented using a Computer Generated Grid (Kappé, Van Erp & Korteling, 1997). A computer generated grid presents a virtual environment observed from a viewpoint that is identical to that of the RPV (using real-time data on RPV position and (camera-)orientation). Thus, even when the artificial grid differs from the remote environment, the optic flow presented is virtually identical to the optic flow that could have been observed on board the RPV. For instance, when an RPV is being driven over flat terrain the camera image presents the actual terrain, while the peripheral image presents a textured ground plane. Since both are registered and generated for the same viewpoint, they present the correct optic flow for the current RPV movements, even when the grid does not present all objects in the remote environment.

5 CONCLUSIONS

The results of the present experiments show that some vehicle control variables and spatial orientation in simulators or in RPV's can be improved by matching display characteristics to the properties of the human visual system.

- Changing the virtual viewing direction is an effective method of increasing the field of regard, but is only effective when the images are presented at their proper position in the optic array, for instance by the use of a head-slaved display or a head-mounted display. Visual information provided by vehicle references about the virtual viewing direction was found to be far less effective under the present experimental conditions.
- A wider field of view improves vehicle control and spatial orientation compared to a small field of view, but the results show that a three-channel display does not need to be rendered at a uniform level of detail. A head-slaved display surrounded by a sparse peripheral image is equally effective as a wide three channel display with a uniform high level of detail.
- Finally, it is cheaper and steering performance is enhanced when only three viewing directions are presented and the head-slaved display is presented stepwise at one display channel (located in the correct direction) at a time instead of being presented continuously moving and thus always exactly in the viewing direction of the observer.

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Dr. B. Kappé
(First author)

Dr. J.E. Korteling
(Project leader)

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11. AUTHOR(S)

B. Kappé, J.E. Korteling, J.B.F. van Erp

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Human Factors Research Institute
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING AGENCY NAME(S) AND ADDRESS(ES)

Director of Army Research and Development
Van der Burchlaan 31
2597 PC DEN HAAG

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))

The images presented in low-cost vehicle simulators and in operator interfaces of Remotely Piloted Vehicles (RPVs) often do not provide enough information for optimal vehicle control and do not elicit sufficient spatial orientation. To improve the effectiveness of these images, the *virtual* viewing direction can be 'head-slaved', or the display can be surrounded with a less detailed peripheral image. Three simulator experiments were used to evaluate the effect of these techniques on steering performance and spatial orientation. In Experiment 1, vehicle references or a head-slaved display provided feedback on the virtual viewing direction. Vehicle references brought about some improvement in lane-keeping performance when a standard 50° × 50° (h × v) display was used. A head-slaved display (50° × 50°) allowed better steering performance, but not up to the levels obtained with a traditional three-channel display (150° × 50°). Experiments 2 and 3 addressed the effects of surrounding the head-slaved display with a less detailed peripheral image, and of moving the head-slaved display discretely or continuously. With the peripheral image (surrounding a head-slaved display), lane-keeping performance (Experiment 2) and spatial orientation (Experiment 3) were just as good as they were with a traditional three-channel display. Performance with the discretely moving head-slaved display was superior to the performance with the more sophisticated continuously moving display. The results show that low-cost simulators and RPV operator interfaces can be equipped with an efficient low-cost display that is just as effective as a normal multi-channel display.

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