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Research Article

Effects of Glare on Elder Drivers' Behavior and Visual Exploration in a Nighttime Driving Simulator

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Abstract

Purpose: The purpose of this study was (i) to evaluate the impact of glare on lane keeping, speed keeping, and head and gaze movements using a state-of-the-art night-driving simulator, and (ii) to assess interindividual variability of the above-mentioned variables.

Subjects and Methods: Fifteen (five female) ophthalmologically healthy participants (age 54.6 to 80.6 years) were asked to maintain an ideal course on a virtual country road, with and without glare from simulated oncoming headlights. Participants were additionally required to detect hazards and optotypes (Landolt Cs with varying contrast levels), displayed directly to the right of the roadside. Lane and speed control metrics were extracted from the simulation software. Gaze movements were expressed as the proportion of gaze points registered towards the right side of the road. Head movements were quantified as the median distance from the head's centroid position in 3D space.

Results: The addition of glare did not cause significant changes in lane keeping (deviation from ideal lane position) or eye movements (the distribution of gaze locations), but did increase the extent of evasive head movements (head median centroid distance) from a median {IQR} value of 3.7 {3.3} mm at baseline (static conditions, no glare exposure) to 9.4 {14.6} mm under dynamic conditions and glare exposure (P=0.023).

Conclusions Within this simulated environment, glare exposure significantly increases the extent of (evasive) head movements but has no significant effect on eye movements or lane keeping.

Keywords: Glare; Visual exploration; Lane keeping; Speed keeping; Night driving; Driving simulator

Introduction

Glare is a 'hindrance to vision by too much light' [1]. It can be subdivided into *disability glare* ("glare that impairs the vision of objects without necessarily causing discomfort") and *discomfort glare* (glare that causes discomfort without necessarily impairing the vision of objects") [2,3]. Disability glare is often used synonymously with *straylight* (the perceived spread of light around a bright source) [4]. A brief outline regarding the history and terminology of glare is given in the Supplementary Material of the present paper. How glare effects road safety is a subject of significant public interest. Featherstone et al. [5] used the Iowa driving simulator to assess driving performance under three visibility conditions (clear weather at night, clear weather at night with glare and fog). Recognition rates/distances for (traffic) signs and hazards were measured, as were hazard avoidance behaviors.

Ranney et al. [6] used a fixed base simulator, simulated following-vehicle headlights using exterior truck mirrors and light sources with computer-controlled shutters on each side of the driver. Experienced truck drivers were exposed to 30 glare episodes, each lasting 20 s. It was reported that "prolonged exposure to intermittent glare during extended driving did not exacerbate performance impairment", which again appears *prima facie* inconsistent with the results of the present study. This again may be due to differences attributable to the way of glare induction. Peli et al. [7,8] developed a dynamic simulation of glare from the headlight by superimposing a bright LED display through a beam splitter on the simulator screen and synchronizing the position of the illuminated LED to the image of the simulated car. This setup was used to measure the impact of glare on pedestrian detection by normal-vision subjects with simulated

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mild cataracts and by patients with real cataracts [9]. Peli et al. found a substantial negative effect of oncoming headlight glare even with mild (simulated or real) lens opacities. Glare led to lowered pedestrian detection rates and longer response times compared to otherwise identical scenarios without glare, which is qualitatively consistent with the results of the present study, although the type of induced glare and the visual tasks differed. The beam splitter option was not used in the current study as according to the authors impression this otherwise elegant approach may be associated with the occurrence of ghost images, as visible in some video clips obtained with this setup.

Melcher et al. [10] used pairs of numbers, presented in a speed limit sign, and induced glare through a pair of mobile LEDs in their fixed-base driving simulator. These LEDs mounted in the plane of the front windshield could have affected the realism of this experimental setup, as the distance between the test subject and the LEDs was rather short and numerical optotypes are known to differ markedly between digits (see e.g., Wesemann et al). [11] Unfortunately, we were unable to locate any quantitative data using this glare device to directly compare the results of the present study.

Recently, Haycock et al. implemented high intensity LEDs, mounted on a robotic actuator, in moving base simulator at the Toronto KITE Research Institute. [12] To our knowledge, results from this experimental glare simulator are unpublished at present.

Our own previously published experimental findings, using the Aalen night-time driving simulator, showed that contrast sensitivity and low contrast visual acuity predicted night-time hazard detection ability in a manner that conventional high contrast visual acuity did not. Either might therefore be considered useful metrics for assessing the ability to drive at night, particularly in older individuals. Conversely, the measurement of intraocular straylight was found to be a poor predictor of visual function and driving performance [13,14].

To the authors' knowledge, the publications available to date focus primarily on the effect of glare on the detection/recognition of objects/obstacles, or on its effects in terms of accident frequencies. So far, there is no reliable information on the influence of glare on measurable variables that allow driving and visual exploration behavior to be operationalized under standardized conditions *without* using psychophysical measurement data. Therefore, the purpose of this study was (i) to evaluate the impact of glare on lane keeping and speed keeping as well as on head and gaze movements in a standardized nighttime driving simulator setting, and (ii) to assess the inter-individual variability of the above-mentioned variables.

Methods

Participants

The participants and apparatus of this study are described in detail elsewhere. [13,14] In short, 15 ophthalmologically healthy adults (five females), aged 54.6 to 80.6 (median 67.2) years participated. Inclusion criteria were as follows: Minimum binocular distance acuity with habitual correction under photopic conditions equal or better 0.3, maximum spherical ametropia ±5 dpt, maximum cylindrical ametropia 2.5 dpt, no more than moderate lens opacity according to the LOCS III core, [15] no self-reported eye disease (e.g., ophthalmic injuries or inflammations, visual pathway diseases, ocular motility disorders or double vision), and no history of ophthalmic surgery (e.g., for cataracts).

Participants were recruited by email advertising within the Aalen University of Applied Sciences, local newspaper advertisements, and by private ophthalmologists.

Written informed consent was obtained from each tested subject. The study followed the principles of the Declaration of Helsinki and subsequent updates. The study protocol and its amended version were approved by the Institutional Review Board of the State Medical Association of Baden-Württemberg (F-2015-044# A2). The original study protocol was approved by Clinicaltrials.gov (NVT03169855; last update January 08, 2019).

Night driving Simulator

The fixed base night driving simulator at Aalen University of Applied Sciences accommodates a modified, fully equipped Audi A4 (Audi AG, Ingolstadt, Germany), with a digital dashboard. Images were projected by two high-performance LED planetarium projectors VELVET LED (Zeiss AG, Jena, Germany) onto a cylindric projection screen (radius 3.2 m). The virtual night driving scenario was generated using the SILAB software package (Würzburg Institute for Traffic Sciences, Veitshöchheim/FRG). This set-up was used to simulate a night driving scenario, featuring a straight rural road (see Figure 1).; for further details, see Appendix and Ungewiss et al. [14] Treutwein, [16] and Bach. [17].

After a careful instruction, all participants completed an approximately three-minute test drive on the virtual, straight test track in order to familiarize themselves with the speedometer and with the operation of the vehicle, its steering, acceleration,

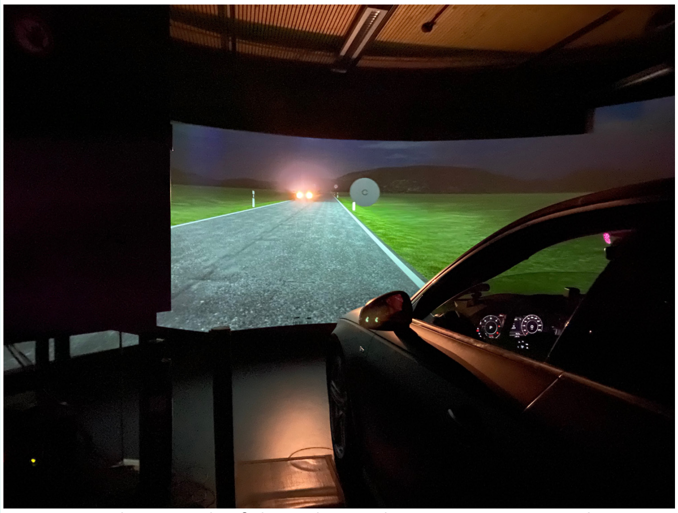

Figure 1: Photograph of the Aalen Night-Time Driving Simulator: The housing of one of the two LED planetarium projectors is visible at the left upper corner, the car (AUDI A4, right lower half of the image) is facing the hemi-cylindrical projection screen, with a LANDOLT C on the right side of the straight rural road. Two cable robots with moving LED glare sources simulate the headlights of the virtual vehicle in the oncoming lane.

Table 1: Lane keeping (rms deviation from the lane center in m, *optotype* presentation RMS = Root Mean Square; IQR = interquartile range; CI_{95} = 95% confidence interval; statistical analysis: two-sided; Wilcoxon test for paired samples. No significant deviations from the baseline (leftmost column: no glare, no optotype) were observed at P = 0.05.

RMS deviation from the lane center [m] *optotype presentation*	**No glare** *no optotype*	**No glare** *optotype*	**with glare** *before optotype*	**with glare** *optotype*
Median {IQR; (CI_{95})}	0.43 {0.67; [0.24, 1.00]}	0.42 {0.69; [0.21, 0.98]}	0.40 {0.11; [0.28, 0.48]}	0.44 {0.09; [0.37, 0.48]}

and braking behavior, as well as the acoustic feedback of the virtual speed-dependent engine noise. Each participant was then faced with a total of four experimental conditions (with 22 trials, each): (i) static with glare; (ii) static no glare; (iii) dynamic with glare; (iv) dynamic no glare. In *static* viewing conditions (with and without glare), the simulated participant vehicle was parked at a distance of 50 m from a stationary oncoming vehicle in the opposite lane. In the *dynamic* viewing condition (with and without glare), the participant first accelerated the simulated vehicle to a virtual speed of 90 km/h and was asked to maintain this speed as accurately as possible; for further details, see Appendix. For reasons of inter-subject comparability, all four experimental scenarios were performed in the same sequence, starting with the static conditions. Glare scenarios were always presented at the end of the test series in order to avoid bias due to afterimages or re-adaptation processes.

Outcome Measures

Speed and lane keeping were evaluated by comparing the recorded logs of various vehicle parameters with the local speed limit and lane center. For most of the tasks (optotypes with glare, obstacles with/without glare), the periodic stimulus presentations started at a distance of 50 m to the glare source, and we compared the Root Mean Square (RMS) deviations (e.g., in speed and lane position) in the 50 m before and the 50 m after the start of the stimulus presentation. Data were sampled by the simulator at 60 Hz, and for each sample we determined (i) the squared difference between the current vehicle speed and the speed limit and (ii) the squared difference between the current lateral vehicle position and the lane center. We summed up those differences for each of the two sections and computed their square root to arrive at the resulting RMS value. For the optotype tasks without a glare source, we presented stimuli continuously at fixed time intervals and compared the performance during the presentation to that in the interstimulus periods (Figure 2).

Eye and head movements were recorded by the integrated (contactless) eye and head tracking system Smart Eye Pro (three tracking cameras, all with a sampling rate of 120 Hz, and one scene camera, with a sampling rate of 25 Hz; SmartEye, Göteborg, Sweden) and aligned /synchronized with the stimulus presentation and vehicle location. We derived and compared the following eye-tracking-based measurements for each scenario:

- The relative gaze point annotation is the percentage of gaze points (eye-tracker samples) that were directed at the stimulus presentation area (with 100% meaning 'driver looked only at the stimulus' and 0% meaning 'driver never looked at the stimulus').

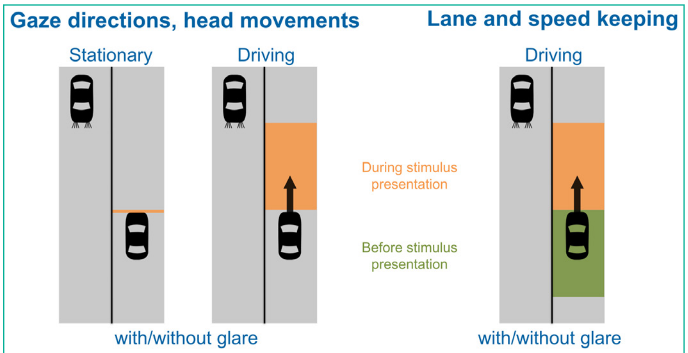

Figure 2: Test sets for stationary and driving scenarios with and without glare. In the stationary test sections, the participant's car remained in a fixed position in front of the glare car. In the driving tasks, the participant moved past the glare car during the stimulus presentation. Lane and speed control were only relevant for driving tasks and were compared for sections of equal length before and after the start of the stimulus presentation.

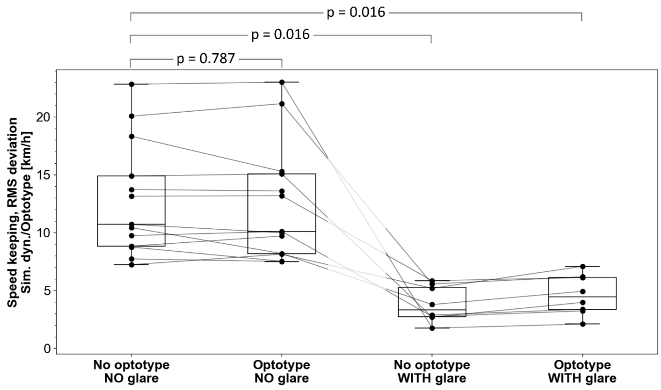

Figure 3: Box-and-whisker plots showing deviations from the specified driving speed ("speed keeping") with and without simultaneous optotype presentation, and with and without glare. The lower and upper limits of the 'box' indicate the position of the 25th and 75th percentile, respectively, and thus represent the 'interquartile range' (IQR); the enclosed horizontal line within the box visualizes the median. The whiskers represent the range of the data (with data points outside the IQR by a factor of 1.5 or more considered outliers); additionally, the individual results are shown as black dots (local overlaps of dots are possible): Grey lines connect the corresponding results of a single participant (WILCOXON test).

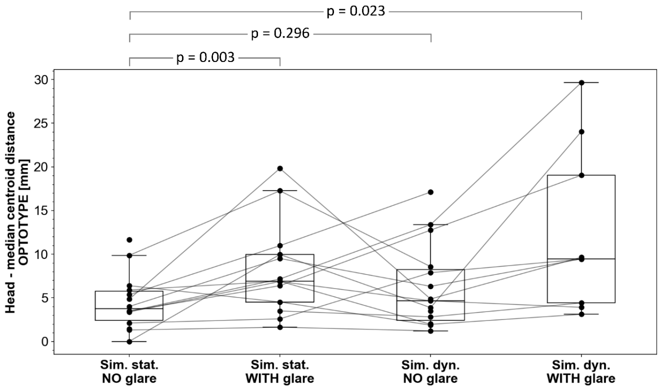

Figure 4: Visualization of the magnitude of head movements during the presentation of a Landolt C stimulus for the static and the dynamic case, respectively, *without* and *with* glare. The median distances of the head positions from their center point in millimeters are analyzed. For further details, see Figure 3 and Table 6, Appendix.

- The median centroid distance is the median of the distances of all head position samples from the mean position of the head position point cloud (the point cloud's centroid). This is a measure of the size of the point cloud and thus of the intensity/amplitude of head movements.

- The median velocity is the median velocity of head movements. A uniform filter over a 0.2 second window is applied before computing the velocity to filter out jitter.

- The distance travelled per minute is the total path length of all head movements normalized to the driving time.

- The median signed centroid distance is the median of all signed distances of head positions from the head position centroid position along the three coordinate axes left/right, down/up, and forward/backward. This indicates whether the median position has a bias towards one side of the centroid.

The datasets were analyzed and visualized in Python using

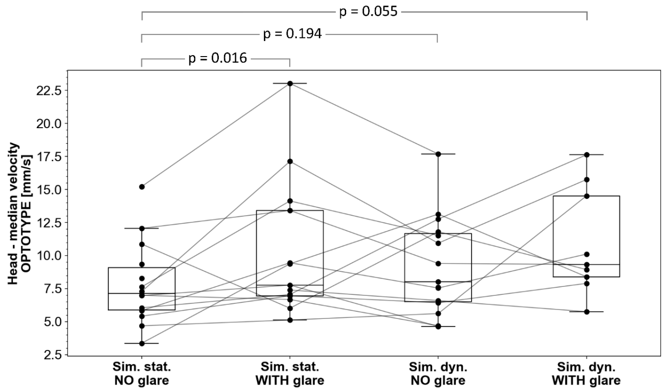

Figure 5: Visualization of the velocity of head movements during the presentation of a Landolt C stimulus for the static and the dynamic cases, respectively, *without* and *with* glare. The median velocity of the head movements (after smoothing with a uniform filter over a 0.2 s window) is analyzed. For further details, see Figure 3 and Table 6, Appendix.

the NumPy and Matplotlib packages [18,19].

Statistical Analysis

The deidentified data sets were analyzed and visualized using the statistical software JMP 16 PRO (SAS Institute GmbH, Heidelberg, Germany) as well as R (Version 4.1.0, GUI 1.76, R Foundation for Statistical Computing, 2021). Because not all data were normally distributed (according to the SHAPIRO-WILK test), nonparametric descriptive statistics (e.g., median and interquartile range = IQR) and inferential hypothesis tests (e.g., WILCOXON test) were employed.

Results

All subjects successfully completed the virtual driving tests without signs of simulator sickness. The median {IQR} durations of the test sections were 108 {21} s (static, without glare), 119 {23} s (dynamic, without glare) 105 {31} s (static, with glare) and 1066 {51} s (dynamic, with glare). The duration of the dynamic test with glare was much longer because the stimuli were only presented when passing the glare car with correspondingly longer pauses in between.

As shown in Table 1 and Table 5, Appendix, deviation from ideal course (“lane keeping”) remained largely unaffected by the presence/absence of glare or the presence/absence of a dual optotype-recognition task, individually or in combination (all $P > 0.05$). The only noteworthy feature of the data was that the deviations from the ideal course showed a much smaller inter-individual variability (IQR) in the glare condition. This likely represents a training/familiarization effect, since glare conditions were always tested second, after the no-glare conditions.

As shown in Figure 3 (and Table 2, and Table 5, each in the Appendix), under night driving conditions without glare, the median {IQR} deviation from the target speed ('speed retention') was 10.7 {6.1} km/h in the baseline condition, and 10.1 {6.9} km/h *with* optotype presentation: a difference that was not significant (WILCOXON test). In subsequent exposure to glare, the deviations from target speed improved significantly from 3.3 {2.5} km/h *before* optotype presentation, to 4.5 {2.8} km/h *with* the presentation of the optotype. This is counter to what one would intuitively expect and again was presumably due to a sequence/learning effect.

Without glare, the proportion {IQR} of gaze movements directed at optotypes decreased from 54% {74%} to 42% {41%} during virtual driving compared to the static baseline scenario (Table 3, Appendix). Adding glare resulted in an increase from 54% {74%} to 67% {53%} compared to the baseline. Adding both glare and virtual driving showed a decrease to 35% {27%}. None of the changes were statistically significant, as indicated by the 95% confidence intervals given in Table 3 in the Appendix.

As shown in Figure 4 without glare, the median distances of the head centroids during optotype presentations increased slightly from 3.7 {3.3} mm to 4.7 {5.8} mm during virtual driving compared to the baseline scenario (static conditions without glare; see Table 4 line 1, Appendix). Adding glare resulted in an increase from 3.7 {3.3} mm to 6.9 {5.9} mm in the static case, and from 4.7 {5.8} mm to 9.4 {14.6} mm in the dynamic case – a factor of 2. In both the static and dynamic cases, the increase during glare exposure (compared to the static baseline scenario without glare) was statistically significant (WILCOXON test). A direction-specific subanalysis of the median centroid distance (horizontal = left/right, vertical = down/up, orthogonal = forwards/backwards) did not show a significant effect of glare exposition (Table 4, line 4-6, Appendix)

The median velocity of head movements during optotype presentations (Figure 5, Table 4 line 2, Appendix) was lowest under baseline conditions (static conditions without glare). It increased from 7.1 {3.2} mm/s to 8.0 {5.2} mm/s during virtual driving compared to the baseline scenario (static conditions without glare). The addition of glare resulted in an increase from 7.1 {3.2} mm/s to 7.8 {6.5} mm/s in the static case, and to 9.3 {6.1} mm/s in the dynamic case. Glare exposure thus induced a significant increase in the median velocity of head movements during glare exposure under static conditions only.

Figures 6, 7 and 8 (see Appendix) show the median head centroid distance over time for three selected participants (those with the lowest, median, and highest median centroid distance). All cases show a certain coincidence of stimulus presentations (dashed vertical lines) and sudden head-excursion spikes.

Discussion

In summary, in a well-standardized nighttime driving simulator environment, lane keeping was not significantly influenced by glare. Speed keeping actually appeared to improve in the presence of glare, but we attribute this to a practise effect. (Interestingly, such learning effects seem to be task-specific and were restricted to speed-keeping within the scope of this experimental setting.) Glare exposure significantly increased the extent of (evasive) head movements, but did not have a significant effect on eye movements.

Relationship of the Present Results with Previous Road Driving Studies

As in the driving simulator studies described in the Introduction, the vast majority of on-road experiments under glare exposition assessed measurement variables primarily related to *visual function*. The de Boer scale is used for a subjective rating of 'psychological glare' or 'discomfort glare'. [20] Applying this scale and a self-developed 'psychological glare factor' Schiller et al. could not identify a significant difference between halogen and LED headlights. [21] They found that the headlight optics used, the age of the person tested, and the glare illuminance made a clearly demonstrable contribution the subjectively perceived glare.

Van Rijn et al. compared clinically established methods for measurement of glare with a self-developed computer-implemented straylight meter and found “a better resistance to fraud for the latter device”. [22] With respect to disability glare van den Berg et al. introduced this method 'for the evaluation of glare-related obstacles during driving', 'to target complaints', and as an 'aid in decision-making regarding cataract surgery'. [23] They established quantitative cut-off criteria for different media opacities and age groups. Wood et al examined “Drivers´ ability to recognize pedestrians at night” in an instrumented vehicle along a closed road course at night in the presence and absence of headlamp glare. They found a degradation of pedestrian recognition by even moderate visual impairments. This was the case, “even when the drivers´ ability mean visual acuity meets licensing requirements” [24].

On the other hand, *driving habits* additionally depend on vehicle-related (suspension, shock absorption, headlights/ lighting systems, speed etc.) and environmental factors (illumination, glare, visibility, weather, road conditions, road course, etc.). Operationalization of this behavior requires quantifying *driving dynamics parameters*, such as lane/speed keeping, or the presence of abrupt maneuvers, manifesting as acceleration peaks along the individual spatial directions and axes (Brooks et al., 2011; Nilsson et al., 2013). [25,26] The paper of Theeuwes et al. is one of the relatively few publications to date that has considered how such *driving behaviors* are affected by glare (i.e., as opposed to exclusively *functional* vision-related measurement variables). The authors generated glare by mounting a low-beam light source on the hood of an instrumented vehicle with the participants driving at night in actual urban, rural, and highway traffic. [27] According to their results, even comparatively low glare levels caused a significant decrease in pedestrian detection and in speed level on dark and winding roads. This effect was most pronounced in the older participants. From the perspective of the authors of this paper this procedure is somewhat artificial, since in this test set-up there was no motion of the glare source relative to the eye of the tested subject. The additional evaluation of *driver activities*, such as head and gaze movements, can provide further insight and have only been considered by a few driving studies to date. Some studies [28-30], however, reported the effect of glare on eye movements when reading. They observed a significant slowing of reading speed due to an increase in fixation duration under 'more adverse' lighting conditions.

Ungureanu et al. attempted to reduce the impact of solar glare on motorists by creating a dark spot in the windshield, “based on smart glass or in-glass transparent displays”; the authors mention the need for knowledge of the driver´s (head and eye) position. [31] Increased head movements when optotypes are presented with glare exposure compared to the non-glare situation in the current study may indicate attempts to evade glare-disable effects by changing the viewing position. The authors of this study did not find a similar effect for obstacles, which may be due to the fact that participants only had to detect the presence of a (relatively fast-moving) obstacle, in contrast to discerning a certain detail (the gap position) in a stationary optotype.

Glare presents a significant challenge for safe nighttime road use. And this challenge is only set to grow as societies age (given that susceptibility to disability glare increases with age). For example, Zydek et al. [32] found that 64% of 509 motorists reported experiencing at least one traffic hazard due to glare, 80% wanted a way to improve their vision during night driving, and more than 60% would be willing to pay more than $400 (USD) for any visual aid that would significantly improve their night vision. Similarly, Hebenstreit et al [33] reported that professional drivers with increased susceptibility to glare are more frequently involved in accidents at night. And Hwang and colleages [9] have shown that even mild cataracts (simulated or real), can result in drivers becoming significantly less able to detect pedestrians in the presence of oncoming headlight glare, both in terms of lower detection rates and longer detection times.

Many of the changes in the aging eye that affect susceptibility to glare also reduce Contrast Sensitivity (CS). It is unsurprising, therefore, that CS (and also low contrast visual acuity) predict aspects of night-time hazard detection ability that conventional high contrast visual does not [34,35]. CS and low contrast visual acuity may therefore provide useful metrics to assess the ability to drive at night, particularly in older individuals. Jones et al. [13] provides a concise compilation of the effects of the ageing visual system and related influencing factors on vision in low light conditions. Featherstone et al. compared bilaterally implanted multifocal Intraocular Lenses (IOL) with monofocal IOLs. The authors found significant differences, with benefits for monofocal IOLs in four of 30 comparisons. None of the significant differences occurred under glare conditions, which is in disagreement with the observations of the current study. This may relate to their particular implementation of headlight glare, which was not described in detail.

In our previous papers we introduced in detail an innovative new simulator that uses robotic lights to precisely recreate the effects of glare from oncoming car headlights. We demonstrated how such a set-up can be used to measure CS with and without glare, [13] and investigated how CS measures correlate with hazard detection performance and intraocular straylight. [14] In the present study we directly investigated how night-time glare affects *driving behavior* (as for instance operationalized by lane or speed keeping) and *visual exploration* (head and eye movements). Such *'external' signals* may be useful driving performance indices that can be monitored passively and without the need for a direct verbal interaction with the tested subjects. So far it remains rather unclear, however, whether and to what extent glare has an influence on driving behavior and on (evasive) head and eye movements.

Study Limitations

First, the sample size of the present study was relatively small. This is especially true for the *dynamic scenario with glare* which suffered from a partial breakdown of the moving glare sources due to a technical defect.

Second, the population of this study is comparatively old and therefore not representative of the entire spectrum of motorist. The accident rate per annual mileage has a typical U-shaped course, with a local maximum for young motorists (below an age of 20 years), which is primarily due to insufficient driving experience; the right leg of the U-shaped course appears in older drivers (above 70 years) most probably indicating age-related restrictions. One of the potential risk factors is glare, which is more problematic for older drivers than younger drivers, which justifies the age selection of this study population. [36] Glare is more problematic for older drivers than for younger drivers, especially due to 'optical' and 'neurological' factors. [37] Obviously, older drivers seem to be aware of this problem, which explains the relatively low proportion of over 65s in nighttime accidents [38].

Third, driving simulators have their own distinct advantages and disadvantages, and in many respects represent a "halfway house" between clinical vision assessments (e.g., of visual acuity) and real on-road driving. In our experience, participants accept the situation as similar to real-world driving to some extent, aided by the fact that while the environment is artificial, the physical car itself is not. This allows us to observe behavior and effects linked to factors that cannot be recreated in a clinical examination. In contrast to real-world driving, the situations encountered can still be precisely controlled and standardized between participants, and safety is not a concern when setting tasks that might distract the driver. Despite high levels of safety and standardization, driving simulator studies are carried out under *virtual reality* conditions and thus need confirmation and validation. For example, the present study was not designed to "demonstrate that increased disability glare is independently associated with either crash involvement or self-reported difficulty in driving", as pointed out by Owsley et al. [39] On-road driving, on the other hand, is highly dependent on external/ambient factors (weather conditions, time of day, lighting/illumination), which cannot be standardized with precision. Such tests are "unnatural"/factitious insofar, as the drivers are aware of the artificial/experimental condition. *Naturalistic driving studies*, as proposed and/or carried out by, e.g. Singh & Kathuria, Huisingh et al. and Owsley et al., use drivers' own cars, equipped with additional hardware to document individual driving behavior and the environmental situation are useful to circumvene the above-mentioned "experimental artifacts". [40-42] This type of studies has the advantage of assessing driving performance under almost everyday, realistic conditions – in most cases in the converted own vehicle [41-44]. However, in this type of driving study standardized, repeatable environmental conditions are difficult to ensure. In the curent experimental setting, a *fixed-base* simulator was used; thus the influence of real ego motion on the execution and control of head and eye movements remains unanswered.

Fourth, all results head and eye movement recordings are valid only within the technical limits concerning the spatial and temporal resolution of the applied components.

Fifth and finally, as usual in clinical examinations, glare experiments were always/generally placed at the end of the series of investigations in this study. This approach is accompanied by the potential side effect/bias of a learning effect. This kind of repetition-/sequence-related effect is described in other psychophysical test conditions [45,46]. Interestingly, such learning effects did not consistently occur in this series of experiments and thus seem to be task-specific: While speed keeping showed such a pronounced learning effect, this phenomenon of sequence-related improvement did not appear with experimental variables like lane keeping, gaze, and head movements, despite an otherwise identical experimental setup. Future experiments should offer driving scenarios without and with glare in randomised sequence at adequate temporal intervals: Intervening time intervals of 30 - 60 seconds should provide sufficient readaptation that is also realistic with respect to actual night driving.

Conclusion

This paper highlights the potential of sensor-enhanced driving simulators to precisely quantify driving dynamics and driver activities in different driving scenarios. Within this simulated environment, glare exposure significantly increases the extent of (evasive) head movements but had no significant effect on eye movements or lane keeping.

Author Statements

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Conflicts of Interest

Michael Wörner is Managing Director of Blickshift GmbH, Stuttgart/FRG. Ulrich Schiefer is consultant of Haag-Streit AG, Köniz/CH. Judith Ungewiss has received a doctoral fellowship with funding from the Ministry of Science, Research, and Arts Baden-Wuerttemberg as part of the HAW-Prom program. She is an employee at both Aalen University, Aalen/FRG, and Carl Zeiss Vision International GmbH, Aalen/FRG. Ulrich Schiefer and Judith Ungewiss received a speaker award from AMO Ireland (affiliated to Johnson and Johnson Vision). Ulrich Schiefer, Michael Wörner and Judith Ungewiss are co-inventors for several patents /patent applications.

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APPENDIX

Night driving simulator – Supplement

The total width of the lane (both own lane and oncoming lane) was 6 m. In order to ensure real-world nighttime and glare conditions, spot luminance procedures were executed prior to the experiments, using the Spectroradiometer CAS 140 VIS/UV (Instrument Systems GmbH, Munich, Germany) and the Minolta Luminance Meter LS 160 (Konica Minolta Holdings K.K., Tokyo, Japan). Depending on the virtual distance (range 10-40 m), the apron within this simulator setting varied between 1.3 and 2 cd/m^2 for the right and between 0.6 and 1 cd/m^2 for the left side of the road, respectively. Two calibrated LED arrays with filter attachment, moved by cable robots, simulated static as well as dynamic glare conditions, corresponding to trajectories, viewing angle (7 to 20 degrees) and illuminance characteristics (0.04 to 1.35 lux) of an approaching Golf/Rabbit VII (Volkswagen AG, Wolfsburg, Germany.

The speedometer (with digital and pointer display) indicated their current speed, and the virtual engine sound playing inside the passenger compartment served as additional acoustic feedback. After covering a distance of approximately 550 m at this speed (i.e., ~22 seconds, that also corresponds to the re-adaptation after being exposed to glare), the participant was prompted by a road sign to reduce their speed to 60 km/h. An approaching vehicle with low beam headlights ("glare generating vehicle") was located 350 m after this sign. 50 m before passing the glare car, an 8AFC Landolt C stimulus was presented. The participant then continued for another pass, and the threshold algorithm proceeded in the same manner as in the static condition. For the tasks without glare, no oncoming vehicle was simulated, and the Landolt C stimuli were instead presented continuously, with a 2-second interstimulus time, so as not to drag out the experiment time unnecessarily. The headlights of the glare generating vehicle were simulated by two LED arrays, which were moved precisely along realistic trajectories by means of cable robots. The LEDs were additionally adjusted in terms of their illuminance (0.04 lx to 1.35 lux) and angle of view (-20 degrees and -7 degrees) in order to precisely replicate the characteristics of the low-bream headlights of an approaching VW Golf VII (Volkswagen AG, Wolfsburg, Germany). In case of *static* glare exposition, the LED arrays were positioned in front of the static (parking) car at the oncoming lane at adequate eccentricities, angles of view, and illuminance levels. For the assessment of contrast sensitivity, optotypes (8 position Landolt Cs, VA level 1.0 logMAR) with varying contrast were displayed directly to the right of the roadside, presented against a uniform grey circular background (luminance 0.032 cd/m^2).

A maximum likelihood procedure (Best PEST) with 22 trials was applied. [16] [17]

Table 2: Speed keeping (root mean square [RMS} deviation from the target speed in km/h, *optotype* presentation); IQR = interquartile range; CI_{95} = 95% confidence interval; statistical analysis: two-sided Wilcoxon test for paired samples, significant (at $P = 0.05$) deviations from the baseline (leftmost data column) shown in bold

RMS deviation from the target speed [km/h] ***optotype presentation***	**No glare** *no optotype*	**No glare** *optotype*	**With glare** *before optotype*	**With glare** *with optotype*
Median (IQR; CI_{95})	10.7 (6.1; [8.8, 18.3])	10.1 (6.9; [8.1, 15.3])	**3.3 (2.5; [2.7, 5.6])**	**4.5 (2.8; [3.2, 6.2])**

Table 3: Relative gaze point annotation (percentage of gaze points in stimulus presentation area, *optotype* presentation). IQR = interquartile range; CI_{95} = 95% confidence interval; statistical analysis: two-sided. Wilcoxon test for paired samples, no significant deviations from the baseline (leftmost data column) at p = 0.05

Relative gaze point annotation [%] ***optotype presentation***	**No glare *static***	**No glare *dynamic***	**With glare *static***	**With glare *dynamic***
Median (IQR; CI_{95})	54(74; [4, 80])	42 (41; [15, 62])	67 (53; [19, 93])	35 (27; [21, 62])

Table 4: Head movements (median centroid distance [mm], median velocity [mm/s], total distance travelled [mm] per minute of driving, median signed centroid distance [mm], *optotype* presentation) IQR = interquartile range; CI_{95} = 95% confidence interval; statistical analysis: two-sided Wilcoxon test for paired samples, significant (at p = 0.05) deviations from the baseline (leftmost data column) shown in bold

Head movement *optotype presentation*	**No glare *static***	**No glare *dynamic***	**With glare *static***	**With glare *dynamic***
Median centroid distance [mm] Median (IQR; CI_{95})	3.7 (3.3; [2.1, 5.9])	4.7 (5.8; [2.0, 8.6])	**6.9 (5.4; [3.5, 11.0])**	**9.4 (14.6; [3.9, 24.0])**
Median velocity[1] [mm/s] Median (IQR; CI_{95})	7.1 (3.2; [5.8, 9.4])	8.0 (5.2; [6.4, 11.8])	**7.8 (6.5; [6.7, 14.1])**	9.3 (6.1; [7.9, 15.8])
Distance travelled per minute of driving[1] [mm] Median (IQR; CI_{95})	837 (340; [202, 4399])	**766 (627; [552, 1378])**	**1575 (1176; [391, 2435])**	**875 (661; [460, 1656])**
Median signed centroid distance (bias) left/right [mm] Median (IQR; CI_{95})	0.5 (1.8; [-0.1, 1.8])	-0.0 (0.8; [-0.4, 0.5])	-0.1 (0.9; [-2.9, 0.7])	-0.2 (1.3; [-0.8, 1.1])
Median signed centroid distance (bias) down/up [mm] Median (IQR; CI_{95})	-0.0 (0.2; [-0.1, 0.1])	0.1 (0.5; [-0.2, 0.4])	-0.3 (0.7; [-1.1, 0.2])	-0.3 (0.5; [-0.5, 0.0])
Median signed centroid distance (bias) forwards/backwards [mm] Median (IQR; CI_{95})	-0.2 (1.1; [-1.1, 0.2])	**0.1 (1.5; [-0.4, 1.8])**	-1.6 (2.9; [-3.2, 0.0])	-0.3 (1.2; [-1.2, 4.2])

[1] Obtained after smoothing with a uniform filter over a 0.2 s window

Table 5: p values for the lane center and target speed deviations with regard to the baseline scenario (no glare, no optotype). Statistical analysis: two-sided Wilcoxon test for paired samples, significant (at p = 0.05) values shown in bold

Attribute *optotype presentation*	No glare *optotype*	With glare *before optotype*	With glare *optotype*
RMS deviation from the lane center [m] *optotype presentation*	0.3268	0.1562	0.2969
RMS deviation from the target speed [km/h] *optotype presentation*	0.7869	**0.0156**	**0.0156**

Table 6: p values for the head movement metrics with regard to the baseline scenario (no glare, static). Statistical analysis: two-sided Wilcoxon test for paired samples, significant (at p = 0.05) values shown in bold.

Attribute *optotype presentation*	No glare *dynamic*	With glare *static*	With glare *dynamic*
Relative gaze point annotation [%] *optotype presentation*	0.9515	0.7334	0.8438
Head median centroid distance [mm] *optotype presentation*	0.2958	**0.0034**	**0.0234**
Head median velocity [mm/s] *optotype presentation*	0.1937	**0.0161**	0.0547
Head distance travelled per minute of driving [mm] *optotype presentation*	**0.0067**	**0.0010**	**0.0156**
Head median signed centroid distance (bias) left/right [mm] *optotype presentation*	0.0785	0.1294	0.1094
Head median signed centroid distance (bias) down/up [mm] *optotype presentation*	0.1937	0.0771	0.2500

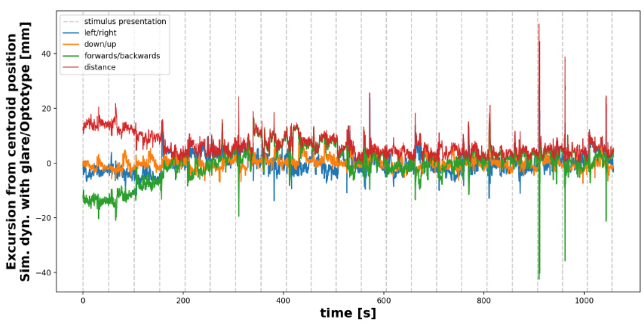

Figure 6: Visualization of the distance in three dimensions as well as the Euclidian distance from the head centroid position plotted over time for the dynamic case with glare exposition. This diagram shows the participant with *lowest* median head centroid distance. Dashed vertical lines mark the start of a stimulus presentation

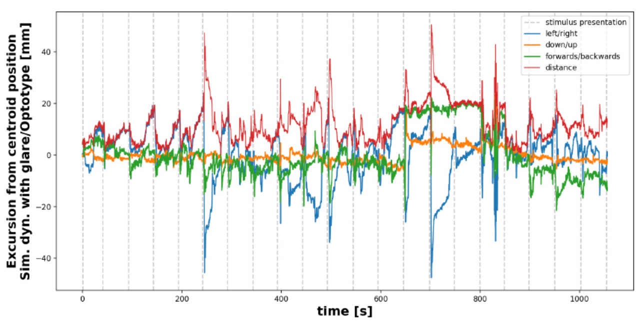

Figure 7: Visualization of the distance in three dimensions as well as the Euclidian distance from the head centroid position plotted over time for the dynamic case with glare exposition. This diagram shows the participant with *median* median head centroid distance. Dashed vertical lines mark the start of a stimulus presentation

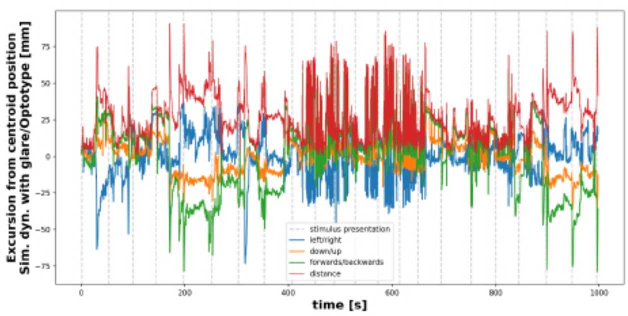

Figure 8: Visualization of the distance in three dimensions as well as the Euclidian distance from the head centroid position plotted over time for the dynamic case with glare exposition. This diagram shows the participant with *highest* median head centroid distance. Dashed vertical lines mark the start of a stimulus presentation