Made available by Hasselt University Library in https://documentserver.uhasselt.be

Influence of straylight on simulated driving performance

Peer-reviewed author version

HERSHKO, Sarah; BRIJS, Tom; Vandebergh, Karel; ECTORS, Wim; Koppen, Carina; van den Berg, Tom; WETS, Geert; Rozema, Jos & ROSS, Veerle (2024) Influence of straylight on simulated driving performance. In: Transportation research Part F: Traffic psychology and behaviour, 103 , p. 96 -111.

DOI: 10.1016/j.trf.2024.03.020
Handle: http://hdl.handle.net/1942/43668

Influence of straylight on simulated driving performance

Sarah Hershko, MD[1, 2,*]
Tom Brijs, PhD[3]
Karel Vandebergh[3]
Wim Ectors[3]
Carina Koppen, MD, PhD[1, 2]
Tom van den Berg, PhD[5]
Geert Wets, PhD[3]
Jos Rozema, PhD[1, 2]
Veerle Ross, PhD[3,4]

1 Department of Ophthalmology, Antwerp University Hospital, Edegem, Belgium
2 Visual Optics Lab Antwerp (VOLANTIS), Department of Medicine and Health Sciences, University of Antwerp, Wilrijk, Belgium
3 UHasselt, School of Transportation Sciences, Transportation Research Institute (IMOB), Martelarenlaan 42, 3500 Hasselt, Belgium
4 FARESA, Evidence-Based Psychological Centre, 3500 Hasselt
5 Neth. Inst. Neuroscience, Royal Academy, Amsterdam, The Netherlands.

Conflicts of interest and source of funding

The authors declare no conflict of interests. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The Royal Academy owns a patent on straylight measurement with Van den Berg as inventor, and licenses that to Oculus for the C-Quant straylight meter.

[*] Corresponding author:

- **Name:** Sarah Hershko, MD
- **E-mail address:** Sarah.Hershko@uantwerpen.be
- **Full postal address:** Van den Nestlei 3, 2018 Antwerpen, België

Keywords

Straylight, glare, driving safety, driving simulator

Abstract

Purpose: This study aimed to investigate how an increase in straylight (*SL*) affects the driving capability of healthy volunteers in various simulated driving circumstances.

Methods: Participants were asked to (virtually) drive along a certain course in a driving simulator in four conditions: a regular drive (baseline), a drive in the presence of a glare source and a drive in the presence of a glare source while wearing two types of straylight filters (*SLF1* and *SLF2*). The driving scenario included six different driving events (e.g. pedestrian crossing the road). The van den Berg straylight meter (*Oculus C-Quant*) was used to quantify the glare experienced by participants.

Results: Twenty-one participants between the ages of *19* and *38* were included. There were significant differences in straylight measurements between the baseline and while wearing *SLF1* and *SLF2* (1.09 ± 0.05, 1.34 ± 0.04 and 1.49 ± 0.02, respectively; ANOVA: $P < 0.001$). Over thirty driving parameters were analysed and significant effects of increased straylight was predominantly observed in the parameters pertaining to the events closest to the glare source (e.g., stationary motorcycle in the middle of the road). In those situations, significant increases in detection and reaction times were observed, as well as in stopping distance. In addition, increased glare hindrance prompted drivers to significantly reduce their speed.

Conclusion: This experiment assessed how straylight, a visual parameter, affects driving behaviour and found that increased straylight leads to impairments in specific driving conditions, but also with some adaptions through compensatory strategies. These observations highlight the importance of straylight measurements to assess driving capability, particularly in those with glare-related impairments.

1. INTRODUCTION

Glare is a common phenomenon when an observer is confronted with a bright light source within a relatively dim background, such as when being blinded by the setting Sun, the headlights of oncoming cars at night, or daylight at the end of a tunnel. In these situations, the observer sees bright, colourful rays emanating from the light source that veils the source's immediate vicinity. This veil causes a considerable loss in contrast and an instinctive need to divert the gaze away from the source, which is often experienced as highly unpleasant. In practice, glare is often described as either discomfort glare, a sensation of annoyance induced by bright sources, or disability glare, where the light causes a reduction in visual quality (Wotton, 2000).

1.1 Causes of glare

Light entering the eye is refracted towards the retina to form an image of the observed scene. Ideally, this means that the image of a small light source, such as a LED, would be projected on the retina as a tiny, luminous point. The optics of the eye are far from ideal, however, and the light can undergo many distortions before reaching the retina. These distortions can be roughly divided into *optical distortions*, local imperfections in the corneal or lenticular shape that cause minor alterations (*±0.02°*) in the light's intended path cause a blurred retinal image, and straylight (*SL*), scattered by microscopic imperfections in the ocular media that cause some light to deviate to spread over angles of *1–100°*, producing the luminous veil over the retinal image. The sources of straylight are located for about *1/3* in the cornea, *1/3* in the lens, and *1/3* in the iris, sclera, and fundus in young, healthy, Caucasian eyes (T. Van den Berg et al., 2010). Moreover, since the internal configuration of these structures alters over time, straylight is strongly affected by age (Rozema et al., 2010, 2015; T. J. Van Den Berg, 1995; T. J. T. P. Van Den Berg, Van Rijn, Michael, Heine, Coeckelbergh, Nischler, Wilhelm, Grabner, Emesz, Barraquer, et al., 2007). With age, the crystalline lens may gradually become clouded due to the formation of small, scattering particles that cause local opacification, a first step towards cataract formation that is directly linked to increased straylight (Rozema et al., 2015). However, even after removing the crystalline lens straylight may still increase with age, albeit at a far slower pace (Łabuz et al., 2017; Rozema et al., 2013), suggesting that there may still be other, yet undiscovered age-related influences. Other parameters of importance are eye colour and skin pigmentation where dark-pigmented individuals typically have less straylight then low-pigmented individuals (T. J. Van Den Berg, 1995), and ocular refraction, where myopic eyes typically have more straylight (Rozema et al., 2010). Since it is dominated by wavefront aberrations, visual acuity does not correlate well with straylight (T. J. T. P. Van Den Berg, Van Rijn, Michael, Heine, Coeckelbergh, Nischler, Wilhelm, Grabner, Emesz, Barraquer, et al., 2007), and both contribute about equally to quality of vision (van der Meulen et al., 2012). This suggests that straylight represents an aspect of visual function that should be considered separately from visual acuity.

1.2 Vision and road safety

Currently, in Belgium, visual acuity in bright and dim conditions and extent of the visual field are considered the primary parameter for the visual assessment of drivers (VIAS, 1998). While important, a focus on visual acuity and visual field alone can be problematic as these are less affected by early cataract (Adamsons et al., 1992; Elliott & Situ, 1998), typically retaining a visual acuity of *20/40* or better (Van Rijn et al., 2002). Since this still meets the legal Belgian requirements, some patients with cataract may drive around day and night without restrictions. But if their straylight would be considered, a clear and unacceptable risk becomes apparent. Since it takes about *10 s* to recover from being blinded, a driver going at *90 km/h* would have travelled a distance of *250 m* with poor visual quality before recovering, leading to dangerous situations as they may not have noticed pedestrians, cyclists, or obstacles on the road across that distance. This is confirmed by traffic accident statistics. Based on data from the U.S. Department of Transportation, National Highway Traffic Safety Administration (*NHTSA*), glare was listed as the critical reason in approximately 17 percent of environment-related crashes. This makes glare the second most common environmental factor contributing to accidents, with slick roads ranking first. The term "critical reason" refers to the immediate reason for the critical pre-crash event, often representing the final failure in the chain of events leading up to the crash, however, it is not meant to be interpreted as the sole cause of the crash or as an assignment of fault to the driver, vehicle, or environment. Out of the 2,189,000 crashes analyzed in the U.S. between 2005 and 2007, glare was identified as the critical reason in 9,000 of these accidents (Singh, 2015). Similarly, in Belgian traffic accident statistics, glare has been linked to an average of *1* accident every *2* days, and approximately *3%* of all traffic fatalities have been associated with glare (Ville de hannut, 2018). These rates are highest in March and October, when sunset occurs around rush hour. Furthermore, the UK Department for Transport recorded in *2017* about *2,639* accidents due to glare (Department for transport, 2014). Since these values only represent the cases where glare could be objectively demonstrated as a cause (e.g. based on the position of the Sun), they most likely underestimate the real magnitude of the issue. This is aggravated by a discrepancy between perceived and actual disability since glare only occurs in the presence of a bright light source, keeping people with increased straylight relatively unaware of the potential danger (Van Rijn et al., 2002). To this end, a recent European consensus paper on visual standards for safe driving advised including glare sensitivity standards (ECOO, 2017). However, as of now, no concrete actions have been taken to implement such standards. The level of straylight that can be deemed safe and the specific driving parameters impacted by glare also remains unclear. In the past, a straylight limit of approximately *log(s) = 1.5*, which is four times the normal value for young eyes, has been suggested, although such a threshold was established on somewhat arbitrary grounds. Additionally, for visually demanding professions such as pilots, a limit value of *log(s) = 1.2* has been proposed, corresponding to an elevation of glare sensitivity by a factor of two (van Bree et al., 2011; T. J. T. P. Van den Berg et al., 2013).

In a driving simulator study, it was observed that the presence of mild (simulated) cataracts had a significant impact on the ability to detect pedestrians crossing or walking alongside the road under oncoming headlight glare conditions (Hwang et al., 2018). However, this study did not establish a direct correlation between the simulated cataracts and specific levels of straylight.

Considering the above, we aimed to investigate how increased straylight levels affects the driving capability of healthy adults in a driving simulator for various driving circumstances. We formulated a hypothesis that anticipated a stronger impact of glare in situations where the critical event occurred in closer proximity to the glare source. The particpants drove in the driving simulator with their own refractive correction, as well as with simulated cataract filters. The findings of this study are expected to contribute to the improved standardization of glare sensitivity, providing healthcare professionals with valuable insights to better advise patients about driving risks associated with glare. By establishing clearer guidelines based on the study's outcomes, healthcare practitioners can offer more informed and targeted recommendations, ensuring the safety of drivers facing glare-related challenges.

2. MATERIAL AND METHODS

2.1 Study design

Because this experiment employed specialized filters to simulate cataracts, it was crucial to only include a younger demographic that naturally have clear lenses and minimal intraocular straylight. Participants were active drivers between the ages of *20* and *40*, recruited from the personnel and students at Hasselt University (UHasselt). The data collected consisted of a general questionnaire on biographical data, such as age, sex, driving experience (i.e., period since obtaining licence) and exposure (i.e., driven distance/week). In addition, the straylight questionnaire (Van Der Meulen et al., 2012) and the Visual Functioning Questionnaire (VFQ-25/NL) (Mangione et al., 2001) were administered for a self-assessment of the visual function by the National Eye Institute (NEI). This was supplemented by a clinical measurement of the subject’s everyday spectacle correction, visual acuity, and straylight. Finally, the volunteers were asked to drive in the driving simulator under different conditions.

This study received ethical approval from the UHasselt's ethical commission (REC/SMEC/VRAI/189/123). Prior to participating, all participants were duly informed about the study's advantages, drawbacks, and associated risks, and they provided informed consent by signing the required documentation.

2.2 Participants

A total of *28* drivers were recruited for the experiment, of which *7* were excluded due to simulator sickness, unreliable straylight measurements, visual acuity ≥ *0.1* logMAR in one or both eyes, language barrier (difficulty in independently filling in the questionnaires in Dutch) or intolerance to the glare source. Therefore, the final sample consisted of *21* participants for whom the descriptive statistics are given in **Table 1**.

Table 1: Demographics	
Total participants	*21*
Male: Female	*11:10*
Mean age	*26.33 ± 1.44 years*
Age range	*19 - 38 years*
Average driving experience	*6.81 ± 1.29 years*
Driving experience range	*< 1 year – 19 years*

2.3 Straylight measurement

Straylight was measured using the Oculus C-Quant, a two-alternative forced-choice compensation comparison straylight meter, which has been thoroughly validated (Coppens et al., 2006; T. J. T. P. Van Den Berg & Coppens, 2015). The output is a logarithmic straylight parameter *log(s)* that represents the ratio of the 'undesired' scattered light that causes retinal contrast reduction, and the 'desired' non-scattered light that forms the retinal image. Higher *log(s)* values therefore correspond with more straylight, and consequently with more severe glare-related complaints. The software also provides quality metrics in the form of a reliability index and an estimated standard deviation (Coppens et al., 2006).

Three consecutive straylight measurements were taken, a baseline measurement with the participant's own correction, followed by measurements while wearing a Tiffen Black Pro Mist filters type *1* and *2* (referred to as *SLF1* and *SLF2*, respectively). These filters approximate the optical characteristics of cataract fairly well, where *SLF1* mimics early cataract (which often prompts people to stop driving at night) and *SLF2* simulates severe straylight hindrance (de Wit et al., 2006).

2.4 Driving simulator and procedure

The STISIM Drive Vehicle Driving Simulator (Systems Technology Inc. Hawthorne, California, USA) that was used is a medium fidelity fixed-base simulator with a force-feedback steering wheel, an instrumented dashboard, brake and accelerator pedals, and with a *135°* field of view 1 (**Figure 1a**). Driving simulation offers the advantage of testing non-existent roadway objects before actual on-field implementation. This method also allows flexible data collection under various traffic and roadway conditions. Furthermore, it provides the means to establish controlled conditions, ensuring that each participant is exposed to identical situations with carefully selected and measurable variable parameters.

In order to familiarize themselves with the simulator participants first performed a practice drive, followed by four experimental rides under different conditions. These conditions consisted of a regular ride (*R*), one in the presence of a continuous glare source (*GS*) and two in the presence of a continuous glare source while wearing *SLF1* and *SLF2,* consecutively. **Figure 1b** shows the glare source used (LED light) from the participants point of view. The glare source had an average illuminance of *40.74 ± 0.50 lx*, measured with the Testo 545 light meter at the observers' viewpoint in the driving simulator, approximately *110 cm* from the LED light. The glare source produced a continuous static light and was positioned just above the horizon in an area where the device itself didn't obscure any relevant details of the scene. The order of the different conditions was randomized to account for learning effects.

Each ride had a duration of approximately *7* to *8* minutes and consisted of six events, again presented in random order. These events were designed to assess various aspects of driving ability. Each drive comprised a *500 m* run-in phase, followed by the six events, each *1000 m* long, separated by four fillers which are road segments of *250 m* without any events. The exception was the event with the traffic light, which was only *250 m* long. Finally, each drive concluded with a *200 m* run-out phase. For data analysis of the general driving parameters such as speed and *SDLP* (Standard Deviation of Lateral Position), a filler segment during which the speed limit was *70 km/h* was selected from each ride.

Figure 1: A. Fixed-base driving simulator; B. Glare source used

2.5 Driving events and parameters

2.5.1 Crossing pedestrian

A man in dark clothing crosses the road from right to left at the zebra crossing (**Figure 2a**). He initiates the crossing when the time-to-collision (*TTC*) is 3 seconds. Hayward, 1972 defined *TTC* as: "The time required for two vehicles to collide if they continue at their present speed and on the same path". A *TTC* of *3* seconds was used to provide drivers with sufficient time to press the brake pedal, following guidelines from the Dutch Institute for Road Safety Research (*SWOV*) (ISA, 2012). According to this source, the braking time at a speed of *50 km/h* (the speed limit in this zone) is less than *3* seconds. The calculation accounts for a "reasonably quick" driver reaction under suboptimal conditions: a constant braking deceleration of *5* m/s^2 and a one-second reaction time on a wet road surface. A short *TTC* was deliberately chosen to prompt drivers to intentionally release the accelerator and quickly apply the brake pedal. This decision aimed to ensure an accurate measurement of the braking time during this event.

2.5.1.1 Driving parameters analysed

Detection time was recorded as time in seconds from hazard onset (in this case, when pedestrian started to cross) to first release of the throttle. The *reaction time* was documented as the time interval between the hazard appearance and the moment of brake activation. While it's challenging to locate typical reaction time values in the literature, one study delineated an average reaction time ranging from *0.6* to *0.7 seconds* for drivers who are attentive, focused, anticipatory of stimuli, and prepared to initiate braking. Notably, the specific age group wasn't specified in this study (Čulík et al., 2022). However, other research has demonstrated that reaction times fluctuate with age (Svetina, 2016). One driving simulator study on participants between the ages of *17* and *25* showed a mean detection time of 0.88 *seconds* and a mean reaction time of *1.2 seconds* (Ross et al., 2015). Regarding *TTC*, this was calculated for the moment when the gas pedal was released (*TTC*-detection time, *TTCdt*) and when the participant pushed on the brake pedal (*TTC*-reaction time, *TTCrt*). The minimum *TTC* (*min TTC*) was calculated as the distance between the hazard and the driver divided by speed. Min TTC is taken as an indicator for the severity of an encounter. In principle, the lower the *min TTC*, the higher the risk of a collision has been. While time-to-collision indicates the level of risk of the timing of the reaction (i.e., late reaction indicates more risk). Various safety limits for time-to-collision can be found in the literature, with *1.5 seconds* being the minimum generally accepted as a critical limit (Van Der Horst & Hogema, 1993; Vogel, 2003).

2.5.2 Stationary motorcycle

A dark colored motorcycle is stationary on a two-lane road waiting to turn left (**Figure 2b**). As participants approach the stationary motorcycle, the event is programmed so that if participants come to a stop within *15 m* from the motorcycle, it remains on the road for an additional 10 seconds. Subsequently, the motorcycle proceeds to drive away by taking a left turn onto a side street. Participants also have the option to overtake the stationary motorcycle.

2.5.2.1 Driving parameters analysed

For each participant, *stop distance* to the motorcycle was determined as the distance at which their speed dropped below *5 km/h*. The motorcycle became visible to drivers starting *150 m* ahead. The calculation for *detection time*, *reaction time* and *time-to-collision* (including *TTCdt*, *TTCrt*, and *Min TTC*) followed the same methodology as applied in the event with the crossing pedestrian.

2.5.3 Following a slow-driving car

A black car enters the main road from a side street and must be followed without overtaking for *400m* (**Figure 2c**). It becomes visible when the headway time in relation to the driver was *5 seconds.* The speed of the car that participants are following is set at *56 km/h*, representing a *20%* reduction from the maximally permitted speed of *70 km/h*. Note that this does not necessarily mean that participants are driving at the same speed.

2.5.3.1 Driving parameters analysed

The measurement of *following distances* was recorded at *10 m* intervals across this *400 m* zone. Subsequently, *mean*, *minimum, and maximum following distances* were calculated based on this dataset. In many European countries, the prevailing traffic safety principle mandates drivers to maintain an adequate following distance from the vehicle in front to prevent collisions in cases of sudden stops or speed reductions. While specific numerical requirements for this distance may not be universally prescribed, a common guideline recommends a minimum of two seconds of separation between vehicles, however, this can vary depending on drivers' abilities, vehicle types, weather conditions, and other factors (Breyer, 2010). For the U.S. the National Safety Council recommends a minimum three-second following distance in good conditions (National Safety Council, 2019).

2.5.4 Left-turn gap acceptance decision

Participants must turn left at an intersection and cross an approaching stream of traffic with increasing distances between each successive car (**Figure 2d**). Participants were instructed not to actually perform a left turn to mitigate the risk of simulator sickness. Instead, they were directed to signal when they deemed it safe to initiate a left turn using the left turn indicator, following the procedure as described in Cuenen et al., 2016.

2.5.4.1 Driving parameters analysed

Left-turn-gap-acceptance decision (LTGAD) refers to the distance gap between oncoming cars, measured in meters. *LTGAD* was calculated based on two parameters, indicator use and throttle use (use of the throttle indicated indirectly that participant had made their choice of turning left and were ready to leave the intersection).

2.5.5 Crossing cyclist

A cyclist rides in front of the participant's car on the bike lane and suddenly turns left (**Figure 2e**). To trigger a braking reaction from drivers, the speed of the cyclist was dependent on the speed of the participant. The cyclist would commence crossing when the driver had covered the first *401 m* of the *1000 m* programmed for this event.

2.5.5.1 Driving parameters analysed

The calculations for *reaction time*, *detection time* and *time-to-collision* were conducted using the same methodology applied in the event with the crossing pedestrian.

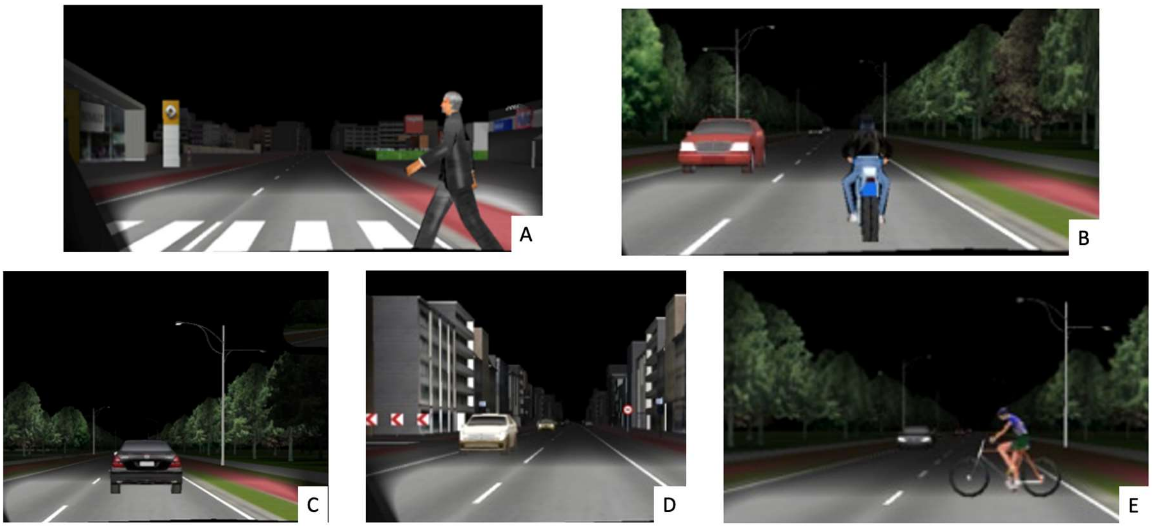

Figure 2: Screenshots of events 1 to 5, A. Event 1, pedestrian crossing; B. Event 2, dark motorcycle stops in the middle of road and is waiting to turn left; C. Event 3, slow-moving dark car; D. Event 4, left turn gap acceptance; E. Event 5, cyclist crossing.

2.5.6 Traffic light

At an intersection with a traffic light, the transition from green to yellow occured when the headway time reached a threshold of *4 seconds*. In an area with a speed limit of *70 km/h*, this should be sufficient to stop safely (Caird et al., 2007).

2.5.6.1 Driving parameters analysed

Reaction time and detection time were carried out employing the identical methodology previously described in the event with the crossing pedestrian. Additionally, the *stop-location* was defined as the distance in meters from the stop line, whith positive values indicating distances before the stop line, and negative values representing distances beyond the stop line.

2.6 Expected influence of glare source on driving parameters

Drawing insights from the literature and the outcomes of a brief initial exploration into participant reactions and experiences, it was anticipated that the glare source would exert varying effects on the different driving events. Based on this initial test, we expected compensatory behavior, such as drivers reducing speed in response to increased straylight hindrance. However, the effects on reaction time, detection time and time-to-collision were expected to vary across events. Notably, as the glare source was fixed at the center of the screen, it was speculated that its effect would be more pronounced on driving events located closer to the glare source. For instance, the event involving the stationary motorcycle, positioned centrally, was expected to be more affected compared to events with objects appearing further away from the glare source, such as the pedestrian emerging from the right side of the screen. Furthermore, *SDLP* was anticipated to be less influenced by the glare source as past studies have indicated that vision impairment tends not to significantly impact *SDLP* (Cordes et al., 2018). Additionally, there is a lack of previous research on the impact of vision impairment on *LTGAD*. In the preliminary examination, no notable impact from straylight was observed for this parameter, leaving the outcome uncertain.

2.7 Statistical analysis

The cohort size was determined based on power calculations, considering the effects of *SLF1* and *SLF2* on increasing straylight (*log(s)*) by *0.29* and *0.48*, respectively, for a standard deviation of 0.1 (de Wit et al., 2006). With $\alpha = 0.05$ and a power of *0.80*, the analysis suggests a cohort size of minimum *20* participants.

Data processing started with a removal of extreme outliers (i.e., any value outside of the ranges: [*Q3 + 3·IQR* and *Q1 -3·IQR*]), followed by the Shapiro-Wilk Test to assess parameter normality. Repeated measures analysis of variance (RMANOVA) was used to compare the means of the driving parameters between conditions (*R*, *GS*, *SLF1* and *SLF2*). The Greenhouse-Geisser correction was applied when sphericity could not be assumed according to the Mauchly's Test of Sphericity. For parameters that were not normally distributed the non-parametric Friedman test was used instead to compare the means. Wilcoxon signed-rank tests was subsequently run as a post-hoc test. All tests were performed using SPSS (v28.0.0.0, IBM) with a significance value of 0.05.

4. RESULTS

4.1 Straylight

Baseline straylight measurement was compared to straylight measurements while wearing the *SLF1* and *SLF2*. The mean straylight value of the right and left eye was used for analysis. There were significant differences in straylight between the baseline, *SLF1* and *SLF2* measurements (*log (s)= 1.09 ± 0.05, 1.34 ± 0.04 and 1.49 ± 0.02*, respectively; $P < 0.001$, ANOVA, **Figure 3**). The straylight measurement for *SLF2* approximates the previously proposed cut-off value for safe driving of *log (s)= 1.5* (Van den Berg, 2017; Van den Berg et al., 2013).

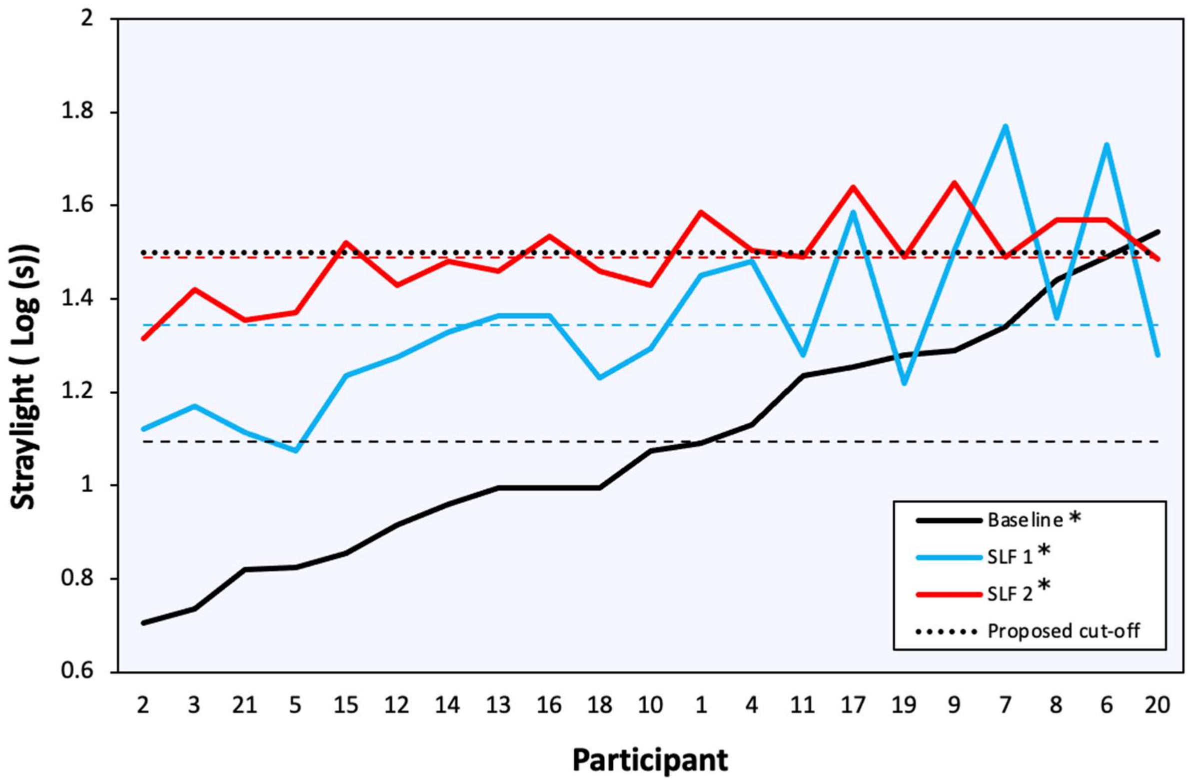

Figure 3: Solid lines: straylight measurement of all participants at baseline and with the straylight filters type 1 and 2, sorted by increasing baseline value. Dashed lines: mean straylight values at baseline and with the straylight filters type 1 and 2. Asterisks indicate statistically significant differences with the other measurements.

4.2 Driving simulator

For every event , specific driving parameters were analysed. An overview of all the driving parameters per event can be found in **Table 2**.

Fillers

A within-subject design with repeated measurements was applied to analyse the general driving parameters during the filler drive. No significant difference in mean *SDLP* between the straylight conditions was found (*P = 0.279*, **Figure 4a**).

Mean speed tended to decrease significantly with the added light source (*P < 0.001*, **Figure 4b**). Post-hoc analysis showed significant differences between all rides except between *GS* and *SLF1* (*P = 0.89*). Minimum speed (*P < 0.001*) and maximum speed (*P < 0.001*) also significantly decreased for *SLF2* compared to the other rides (*P < 0.001*).

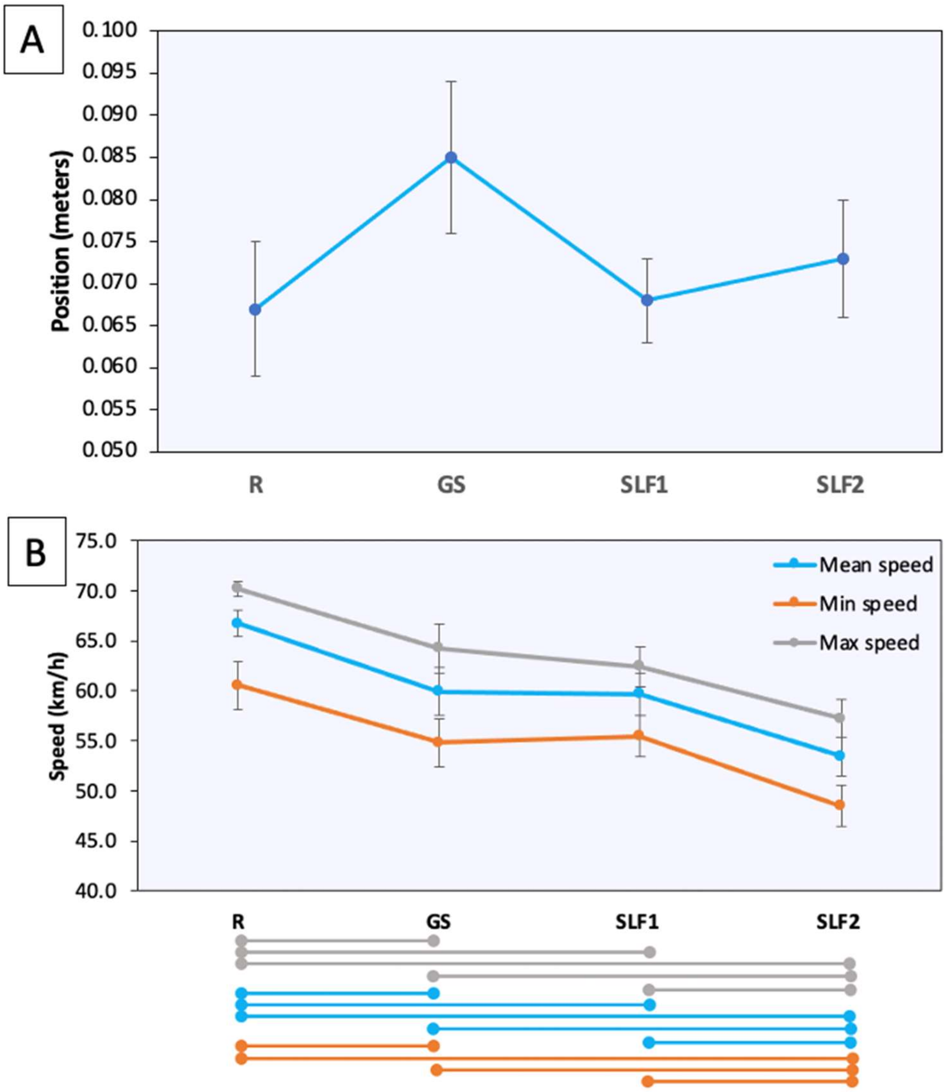

Figure 4: Graphs depicting certain parameters measured during the filler-segments, A. Mean standard deviation of lateral position, with the error bars representing the standard error. No statistically significant differences were observed between the conditions. B. Mean, minumum and maximum speed, with the error bars representing the standard error. The dots beneath the graphs connect the conditions that exhibit statistically significant differences between them. The connected dots are color-coded based on the parameter, corresponding to the colors in the graph's legend.

Crossing pedestrian

The parameters in this event were analyzed using a within-subject design with repeated measurements, with the exception of *minTTC*. This parameter was instead subjected to the non-parametric Friedman test due to its non-normal distribution. Detection time did not differ significantly between the different driving conditions (P = *0.509,* **Figure 5a**). The detection time had a substantial number of missing values from cases in which participants had released the throttle very early on, prohibiting accurate determination. Reaction time was significantly shorter for *SLF2 (1.386 ± 0.122 seconds,* **Figure 5a***)* compared to both *R (1.746 ± 0.077 seconds, P = 0.013)* and *SLF1 (1.869 ± 0.058 seconds, P = 0.001)*, while *TTCrt* was significantly longer for *SLF2* (*1.659 ± 0.121 seconds*) compared to *R (1.203 ± 0.067 seconds*, *P = 0.013*) and to *SLF1 (0.993 ± 0.043 seconds*, *P = 0.001*). The *TTCrt* for *SLF1* was significantly shorter compared to the *TTCrt* of *R* (P= *0.029*). *TTCdt* could not be analysed due to the high number of extreme outliers. No significant differences were found between the rides for *Min TTC* (*P = 0.145*). *TTCdt*, *TTCrt* and *Min TTC* for the regular drive, GS, *SLF1* and *SLF2* are illustrated in **Figure 5b**.

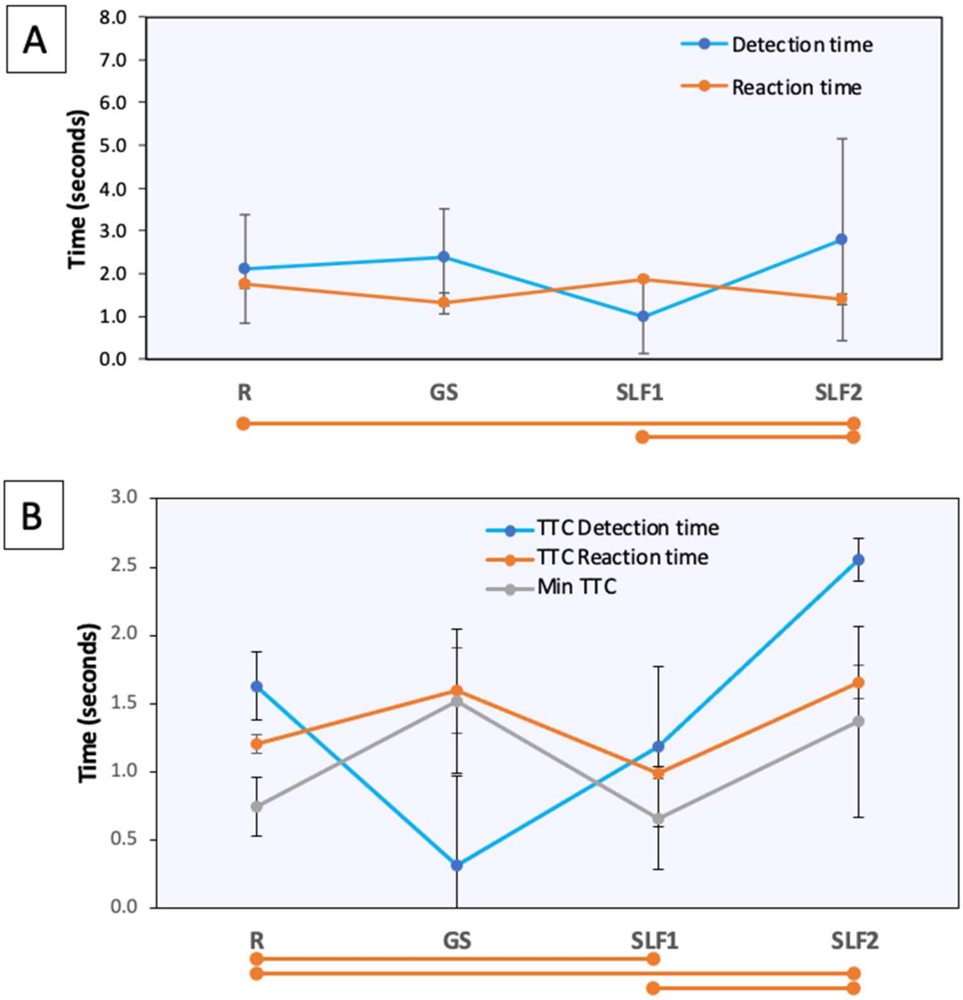

Figure 5: Graphs depicting certain parameters assessed during the event with the crossing pedestrian, A. Detection and reaction time; B. Time-to-collision including TTCdt, TTCrt and Min TTC. In both graphs the error bars represent the standard error. The dots beneath the graphs connect the conditions that exhibit statistically significant differences between them. The connected dots are color-coded based on the parameter, corresponding to the colors in the graph's legend.

.

Stationary motorcycle

In this event, the non-parametric Friedman test was applied to *TTCrt*, *minTTC*, and the stop distance to the motorcycle due to their non-normal distribution. The remaining parameters underwent analysis using a within-subject design with repeated measurements. Detection time significantly increased as glare hindrance increased (P < *0.001,* **Figure 6a**), going from a mean of *0.713 ± 0.221 seconds* for *R* to *7.213 ± 0.368 seconds* for *SLF2*. Post-hoc test showed significant differences between each of the rides except between *SLF1* and *SLF2* (*P = 0.366*). Reaction time also significantly increased with glare (*P < 0.001,* **Figure 6a**), and the post-hoc test showed significant differences between all the rides (*P < 0.001*). *TTCdt*, *TTCrt* and *min TTC* all significantly decreased with added glare hinder (*P < 0.001* for *TTCdt*; P *< 0.001* for *TTCrt* and *min TTC,* **Figure 6a**). The stopping distance to the motorcycle got shorter when straylight hindrance increased (*P < 0.001*) with the mean distance being *21.60 ± 3.27 m*, *13.89 ± 1.31 m*, *5.77 ± 0.90 m* and *3.27 ± 0.16* m for *R*, *GS*, *SLF1* and *SLF2*, respectively. A visual representation of the mean stopping distance is shown in **Figure 6b**.

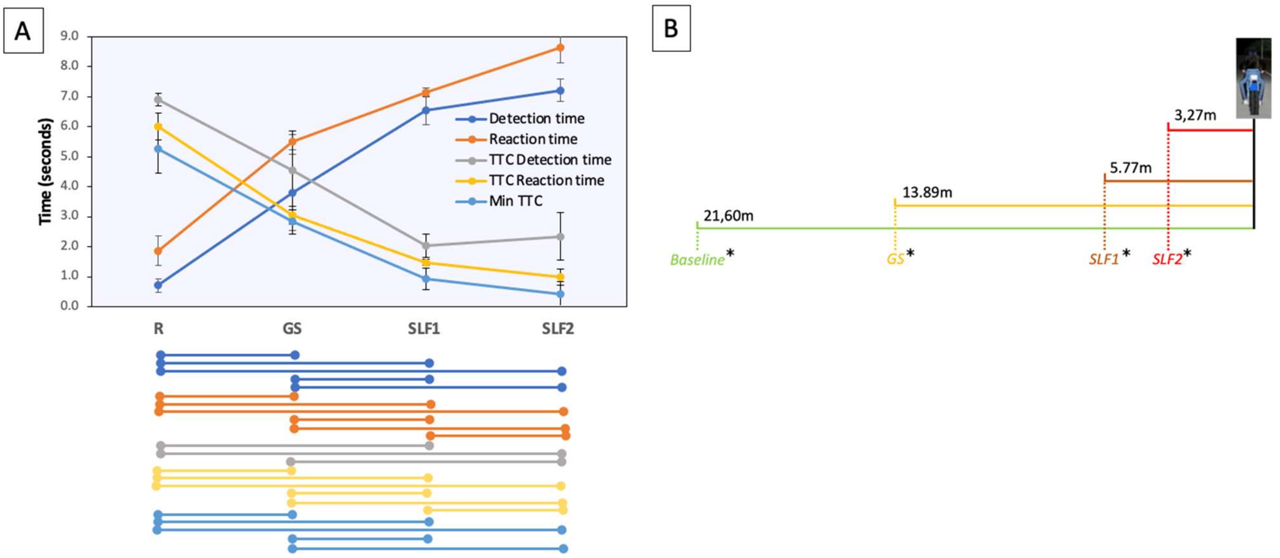

Figure 6: Graph and figure depicting certain parameters assessed during the event with the stationary motorcycle, A. Detection time, reaction time and time-to-collision including TTCdt, TTCrt and Min TTC; The dots beneath the graphs connect the conditions that exhibit statistically significant differences between them. The connected dots are color-coded based on the parameter, corresponding to the colors in the graph's legend.B. Visual representation of mean stopping distance. Asterisks indicate statistically significant differences compared to the other conditions.

Following a slow-driving car

For the analysis of this event, all means were compared using RMANOVA. For the car following scenario, a significantly (*P = 0.005*) higher maximum following distance was observed for *SLF1 (57.57 ± 3.53 m)* and *SLF2 (59.92 ± 3.44 m)* compared to *R (45.88 ± 1.59 m)*. Mean following (*P = 0.162*) and minimal following distance (*P = 0.921*) did not significantly differ between the rides (**Figure 7**).

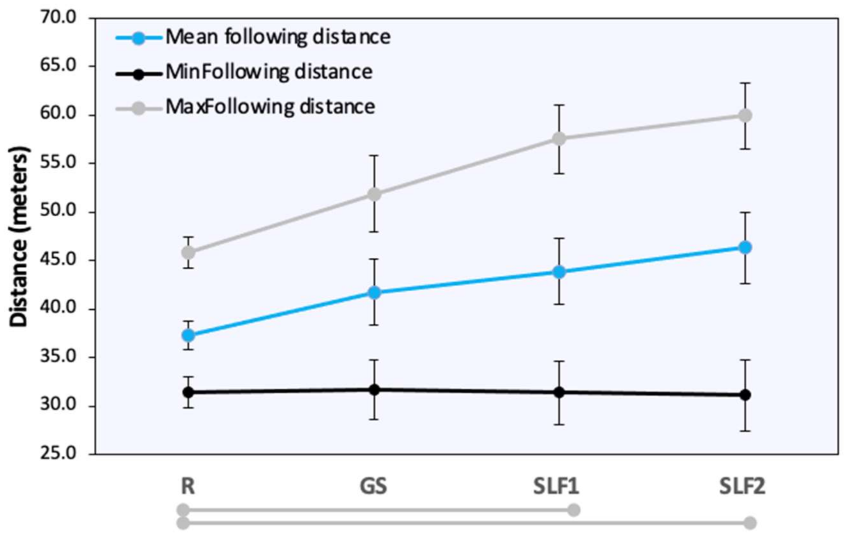

Figure 7: Graph illustrating certain parameters assessed during the event where participants were following behind a slow-driving car, including mean, minimum, and maximum following distances. The dots beneath the graphs connect the conditions that exhibit statistically significant differences between them. Among these parameters, statistically significant differences between conditions were only observed for maximum following distance.

Left-turn gap acceptance decision

There was no significant difference in left-turn-gap-acceptance decision between the rides. The P-values for left-turn gap acceptance based on indicator use and throttle use are *P = 0.176* and *P = 0.156*, respectively. Both were calculated using the non-parametric Friedman test (**Figure 8**).

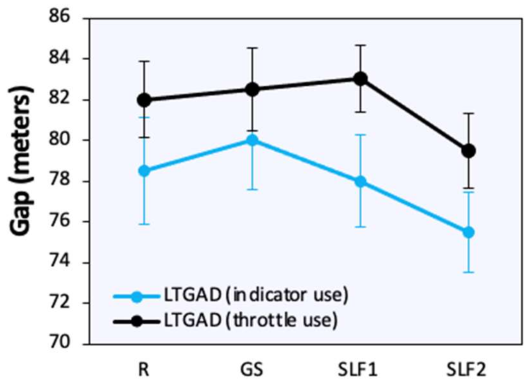

Figure 8: Left-turn gap acceptance decision calculated based on indicator and throttle use with the error bars denote the standard error. No statistically significant differences were observed between the conditions for either parameter.

Crossing cyclist

The cyclist was programmed to cross the road in a *70 km/h* driving zone. In this event, all parameters were compared using the non-parametric Friedman test for analysis, except for *MinTTC*, for which RMANOVA was utilized. Detection time, reaction time and *TTCdt* did not show statistically significant differences between the rides (*P = 0.443*, *P = 0.901* and *P = 0.392* respectively, **Figure 9**). *TTCrt* was statistically shorter for *R* compared to the other drives (*P = 0.003*, **Figure 9**). Similarly, *min TTC* was significantly shorter for *R* compared to the other drives (*P < 0.001*).

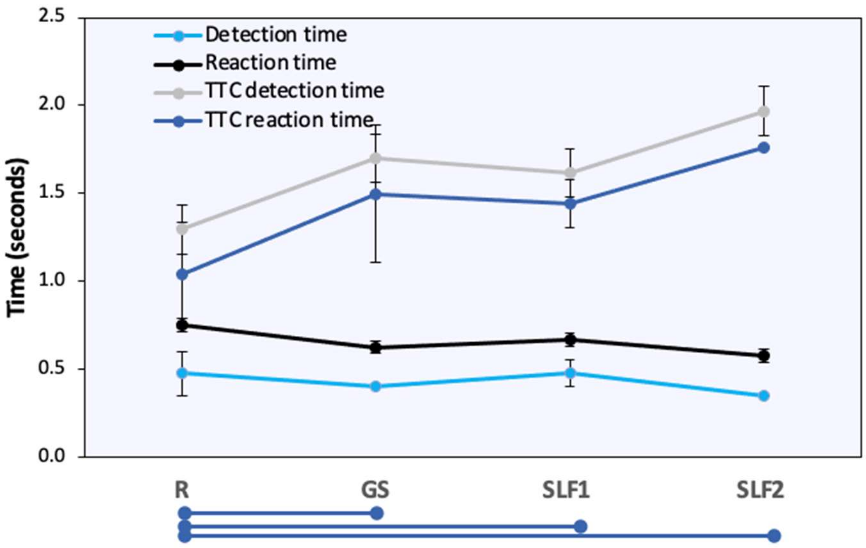

Figure 9: Graph illustrating parameters assessed during the event with the crossing cyclist, including detection time, reaction time and time-to-collision. The dots beneath the graphs link the conditions showing statistically significant differences. Among these parameters, statistically significant differences between conditions were only observed for TTC reaction time.

Traffic light

Each participant stopped for the yellow light in each ride. Stop-location was analyzed using the RMANOVA, while reaction time was analyzed using the Friedman test. Detection time could not be analysed due to the high number of extreme outliers. For this event, no significant difference was detected for reaction time (*P = 0.056,* **Figure 10a**) and stop-location (*P = 0.729,* **Figure 10b**).

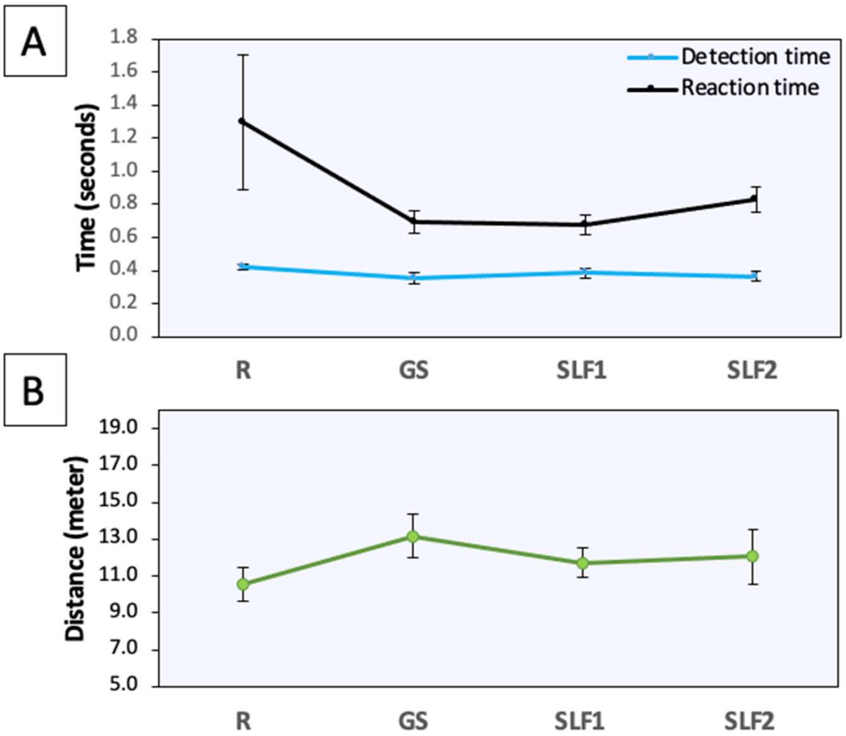

Figure 10: Graphs illustrating certain parameters assessed during the change of traffic light from from green to yellow, A. Detection and reaction time for the different conditions, no statistically significant differences were observed between the conditions; B. Stop-location of the drivers relative to the position of the traffic light, no statistically significant differences were observed between the conditions.

5. DISCUSSION

The current study investigated the effect of straylight on driving performance in healthy volunteers using a driving simulator that simulated real-life driving circumstances. To the best of our knowledge, this is the first time that such an experiment was performed in combination with the Oculus C-Quant straylight meter. Straylight measurement yields precise predictions for the degree of interference caused by glare (T. J. T. P. van den Berg, 2017), making the correlation between straylight values and driving performance practical and valuable for assessing impairment in driving competence due to glare.

As expected, our results demonstrated an impact of increased straylight on driving behaviour in most cases. The response to increased straylight can be divided into three distinct types of responses: 1) compensating driving behaviour, 2) impeded driving behavior and 3) no impact.

First we will discuss the parameters that seem to indicate safer driving behaviour with heightened straylight. For instance, lower reaction time and increased *TTCrt* for *SLF2* compared to *R* and *SLF1* in the event of the crossing pedestrian, increased *TTCrt* with increased straylight in the event of the crossing cyclist and significantly lower speed recorded in the filler segment. In these cases, we suspect that drivers might have used compensatory strategies, which are conscious methods to counteract reduced capabilities (Crepeau et al., 2009) and have been observed among elderly drivers (Milleville-Pennel & Marquez, 2020). Although elderly people experience a decline in visual exploration and cognitive functions, they use compensatory strategies such as driving slower and taking fewer risks when faced with critical events to reduce their risk of being injured. Intuitively, lower speed seems safer, as higher speeds would increase the risk, severity, and fatality of a crash. Some studies argue, however, that the risk of a crash reduces with smaller differences in speed between vehicles in a traffic stream. Hence, while slower driving might lower the severity of a crash, it would not necessarily reduce the risk of a collision (Aarts & van Schagen, 2006; Wang et al., 2013). The observed decrease in reaction time and time-to-collision with increased straylight could potentially be attributed to drivers compensating by redirecting their gaze away from the glare source to expand their visual field, thereby enabling quicker responses to hazards located on the side of the road. Even though the absence of eye-tracking devices in this study limits conclusive findings, similar compensatory strategies (i.e., augmented head movements and the reduction of vehicle speed) are observed in drivers with visual field defects (Coeckelbergh et al., 2002; J. Lee & Itoh, 2020). One of these studies did show, however, that while compensation can somewhat mitigate the risk of collisions, these compensation strategies also have their limitations, as they were unable to reduce the number of pedestrian collisions to the levels seen in drivers with healthy sight (J. Lee & Itoh, 2020). From this, we can deduce that although increased straylight may prompt compensation strategies resulting in, for example, reduced reaction time and increased time to collision, it does not necessarily translate to safer driving situations and reduced risks.

When comparing reaction times across events, we observed that while reaction times shortened with increased straylight, the reaction times for the crossing pedestrian were significantly longer than those for the crossing cyclist under the same conditions ($P < 0.001$, paired samples test). This disparity could potentially be attributed to reduced visibility in the crossing pedestrian, possibly influenced by factors such as dark clothing in nighttime conditions. The observed reaction time to the crossing cyclist closely approximated the values reported in the literature (Čulík et al., 2022).

Second, certain parameters have shown a clear impairment of driving ability, which was particularly evident in the event involving the stationary motorcycle. We hypothesised that increased straylight would affect responses more in events were the critical event occurs close to the source (stationary motorcycle and car following scenario), and less for events farther away from the source (pedestrian, crossing cyclist and left-turn-gap-acceptance). Our findings partially confirm this hypothesis, as evidenced by the parameters of the stationary motorcycle. In this event detection time during the regular drive aligns closely with literature values (Ross et al., 2015). However, with higher straylight levels, it substantially increased, reaching approximately tenfold higher values for *SLF2* compared to the regular drive. In terms of reaction time, the regular drive exhibited a slightly higher value than what is typically reported in the literature (Čulík et al., 2022; Ross et al., 2015). Nonetheless, this value also escalated, reaching up to five times the regular drive's values for *SLF2*. Furthermore, time-to-collision significantly decreased with more glare, falling below the suggested safety limit of *1.5 seconds* for *SLF2*, and in the case of minimum time-to-collision, *SLF1* also dropped below this safety threshold (Van Der Horst & Hogema, 1993; Vogel, 2003). These parameters clearly demonstrate more dangerous driving situations with increased straylight.

Maintaining a safe distance between two vehicles is a critical factor in reducing traffic accidents. While there are no specific regulations governing the distance to maintain when stopping behind an obstacle, it is essential to allow sufficient space between vehicles for several reasons. A greater stopping distance acts as a buffer in the event another vehicle behind fails to stop, provides the driver behind with a better view of the road ahead, and ensures enough maneuvering room in case it's necessary to go around an obstacle. Therefore, the observed reduction in stopping distance with increased straylight levels suggests less safe driving conditions.

Rear-end collisions are the most common type of accidents between vehicles, and they can be mitigated by increasing the following distance. In our event, where drivers were following a car traveling at a speed of *56 km/h*, the National Safety Council advises maintaining a minimum following distance of *31.12 m* (National Safety Council, 2019). Our data shows that even with increased straylight hindrance, the minimum following distance did not significantly change and closely approximated the proposed safety limit. However, as straylight hindrance increased, drivers consistently maintained a notably larger maximum following distance, which can be interpreted as a compensatory strategy. Hence, for this particular event, we can conclude that safe driving conditions were consistently maintained, even when confronted with increased straylight.

Last, certain parameters, such as mean *SDLP* and *LTGAD*, demonstrated no substantial effects resulting from increased straylight. This observation could be attributed to the limited role of visual impairment in influencing these parameters. Consequently, the increase in straylight might result in less noticeable hindrance. A study comparing driving performance of visually impaired and normally sighted individuals also found that visually impaired participants were generally able to control the vehicle's position on a winding road (Cordes et al., 2018). We did not come across any studies that have previously described the connection between *LTGAD* and vision impairment.

5.1 Practical recommendations

Increased straylight in combination with a glare source close to a critical event may lead to dangerous driving situations. For certain parameters, the impact of increased straylight was already noticeable with *SLF1*, corresponding to early cataract (log(s) = 1.34 ± 0.04). With *SLF2* (log(s) = 1.49 ± 0.02), indicating moderate cataract, a diminished driving ability was observed across all parameters. The average straylight value with *SLF2* closely matches the threshold value of *log(s) = 1.50* suggested earlier by van den Berg et al. (2017), indicating that this proposed straylight cut-off value might be too high. Based on the results above, *log(s) = 1.40* might be a more appropriate value. This value corresponds to a more than threefold increase compared to the normal value in young, healthy eyes and is consistent with the mean observed in mild cataract, as determined by the Lens Opacities Classification System III (Michael et al., 2009). To assess how lowering the threshold might affect the driving population, we reanalysed the data of the European Drivers Study by van den Berg et al. (2007) (**Figure 11**). This shows that based on visual acuity alone, none of the drivers over 70 years would be deemed unfit to drive based on criteria of visual acuity (> 0.3 LogMAR). Meanwhile for straylight, lowering the threshold from *log (s) ≥ 1.5* to *log(s) ≥ 1.4* would double the number of drivers deemed unfit at age 70 years, and even triple those at 75 years. Although such a policy change appears to have a major impact on the mobility of people in those age categories, it can easily be mitigated using cataract surgery to bring straylight back to acceptable levels (Łabuz et al., 2015).

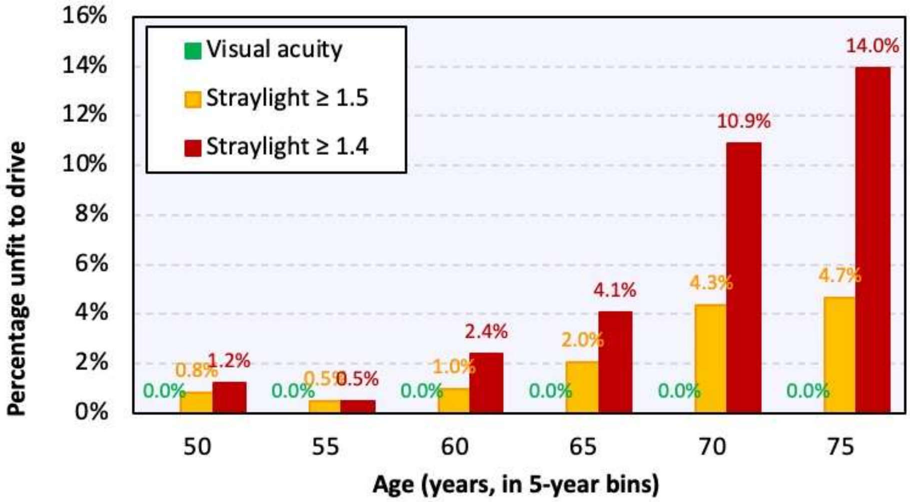

Figure 11: This figure presents the percentage of drivers deemed unfit to drive based on visual acuity (>0.3 LogMAR) and straylight limitations (log (s) ≥ 1.5 and ≥ 1.4) applied to both eyes. (van den Berg et al., 2007)

An important issue is that, despite the significant difference between the straylight measurements (baseline*, SLF1*, and *SLF2*), our results indicate the existence of a spread in the different conditions. For the calculation of a cut-off value, our analysis focuses on the overall averages to derive meaningful conclusions. It is not feasible to consider individual fluctuations, but we underscore the importance of a safety approach that considers the specific situation of each individual. Straylight measurements are currently infrequently used in clinical practice, and rarely to assess suitability to drive. Our results should, in the first place, allow clinicians to better interpret straylight values in relation to driving capability. Older drivers with cataracts more frequently avoid challenging driving situations, such as driving at night, unfavorable weather conditions, highways, and rush-hour traffic. Moreover, individuals with cataracts tend to restrict their driving exposure, reducing their driving frequency and driving range, or stop driving altogether (Ball et al., 1998; Owsley et al., 2001; Owsley & McGwin Jr, 1999). Hence, we recommend that patients with concerns about how glare affects their driving ability should undergo a straylight measurement. This could be supported by a campaign to increase glare awareness and consequently improve driving safety. These results could also facilitate conversations with patients about the optimal timing for their cataract surgery as intraocular lens implantation helps patients to reduce their driving difficulty (Ball et al., 1998; Owsley et al., 2001).

Additionally, implementing a Graduated Driving Licence (GDL), typically applied to young drivers to gradually allow more complex driving scenarios, could be reversed for older individuals by gradually avoiding the most complex situations (e.g., driving at night). This approach may mitigate the significant impacts of tightening cut-off values on patients' travel behavior while ensuring traffic safety. Further research is imperative to optimize the cut-off values for safe driving, as well as to determine the best approach for each level of straylight hindrance (awareness, avoidance of high-risk driving situations, cataract surgery, etc.).

5.2 Limitations

Although the cohort size may appear small, it still has sufficient statistical power due to the use of the filters to increase straylight. We observed that the baseline straylight measurement in this study (*log (s)= 1.09 ± 0.05)* is higher compared to literature data of the general population for this age group (*log (s)= 0.931*) (Rozema et al., 2010). Even so, the driving results can be interpreted within the specified range of straylight and provide valuable insights for clinical practice. Additionally, there is a spread in the straylight values that became apparent after the data collection process. Stratifying participants based on ranges of straylight measures may potentially provide a more precise analysis and warrants consideration in future studies. One limitation of this study was the learning effect since each participant had to undergo the six events four times for the different conditions (i.e., withinsubjects design), making it plausible that some drivers may have anticipated some events and adjusted their driving behaviour accordingly. This was mitigated by randomizing the order of the events in each drive as well as the driving conditions. Nevertheless, future research should consider utilizing different participants for each condition (i.e., between-subjects design).

The validity of driving simulators has been previously questioned as it may stimulate risky driving behaviour due to the absence of the severe consequences of a real collision. At the same time, simulators may also underestimate the same risky behaviour given that many of the real-life distractions present in real traffic (e.g., passengers, phone) are excluded and participants may not have the same degree of motivation in a simulated environment. Despite these issues, simulators have been found to accurately measure speed, lateral position, and hazard avoidance behaviour in controlled, repeated environments without any risk for life or property, and allow rich performance data collection (speed, brake performance, deceleration, collisions, etc.) (Shechtman et al., 2009; Underwood et al., 2011).

Simulating a realistic representation of headlight glare in a driving simulator is challenging and poses a limitation in this study. In this experiment, an LED light was utilized as a glare source to closely mimic modern vehicle headlights. It is conceivable that employing different types of light sources may lead to differing results in this experiment, emphasizing the need for further research.

Moreover, since in this experiment, a continuous glare source was applied, while in reality drivers would be blinded by glare suddenly and for a short time. In this context, visual adaptation might play a role, which is known to impact driving performance. Visual adaptation refers to the process by which the eye adjusts to changes in light levels to optimize vision. A driver's exposure to a wide range of luminance values necessitates rapid adaptation, potentially affecting hazard perception (Plainis et al., 2005).

It's important to acknowledge that in this experiment straylight was artificially increased in a sudden manner, while cataract and aging would only gradually increase straylight, allowing individuals to adapt. However, this gradual progression can also lead to a lack of awareness of the impairment, potentially leading to overconfidence. To address this, our upcoming research will concentrate on older individuals who experience elevated straylight due to the mentioned factors. Comparing the results of these experiments will offer valuable insights into the impact of gradual versus sudden increases in straylight on driving behavior.

6. CONCLUSION

In conclusion, we investigated the impact of straylight on driving performance in healthy volunteers using a driving simulator to mimic real-life driving conditions. Our findings revealed that increased straylight had various effects on driving behavior, with some parameters indicating improved safety under increased straylight conditions. These observations suggest that compensatory strategies may be employed by drivers to mitigate the impact of impaired visibility. However, it's important to note that these strategies have limitations and may not completely reduce collision risks to the levels seen in individuals with normal vision. In contrast, certain parameters, particularly those related to the stationary motorcycle event, displayed clear impairments in driving ability as straylight values increased. This suggests that the effect of straylight on driving may vary depending on the proximity of critical events to the glare source. Our study also raises questions about the proposed straylight cut-off value for safe driving, suggesting it may need reconsideration. Our results provide valuable insights into the assessment of driving capability based on straylight measurement.

	Mean				Standard Error				Shapiro-Wilk test				Comparison		
Filler	**R**	**GS**	**SLF1**	**SLF2**	**R**	**GS**	**SLF1**	**SLF2**	**R**	**GS**	**SLF1**	**SLF2**	**p-value**	**test**	**Mauchly's Test**
Mean SDLP (*m*)	0.067	0.085	0.068	0.073	0.008	0.009	0.005	0.007	0.195	0.503	0.403	0.253	0.279	ANOVA	0.403
Mean speed (*km/h*)	66.730	59.918	59.660	53.440	1.322	2.363	2.106	1.904	0.840	0.182	0.721	0.382	< 0.001	ANOVA	0.969
Min speed (*km/h*)	60.546	54.804	55.430	48.485	2.385	2.430	2.058	2.033	0.256	0.657	0.144	0.476	< 0.001	ANOVA	0.641
Max speed (*km/h*)	70.174	64.224	62.398	57.233	0.756	2.474	1.976	1.855	0.908	0.968	0.972	0.962	< 0.001	ANOVA	0.583
Crossing pedestrian															
Detection time (*s*)	2.097	2.376	0.976	2.785	1.268	1.134	0.862	2.370	0.827	0.105	0.024	0.189	0.509	ANOVA	0.458
Reaction time (*s*)	1.746	1.302	1.869	1.386	0.077	0.257	0.058	0.122	0.210	0.229	0.593	0.287	0.041	ANOVA	0.192
TTC Detection time (*s*)	1.628	0.318	1.187	2.554	0.250	0.652	0.585	0.159	0.451	0.174	0.409	0.115	---	---	---
TTC Reaction time (*s*)	1.203	1.601	0.993	1.659	0.067	0.313	0.043	0.121	0.299	0.413	0.638	0.915	0.026	ANOVA	0.026
Min TTC (*s*)	0.745	1.516	0.662	1.370	0.217	0.526	0.373	0.701	0.597	0.718	0.149	0.045	0.145	Friedman	
Stationary motorcycle															
Detection time (*s*)	0.713	3.808	6.554	7.213	0.216	1.268	0.484	0.368	0.740	0.131	0.262	0.751	< 0.001	ANOVA	0.021
Reaction time (*s*)	1.875	5.500	7.146	8.634	0.502	0.252	0.142	0.511	0.304	0.517	0.492	0.980	< 0.001	ANOVA	0.295
TTC Detection time (*s*)	6.903	4.543	2.044	2.353	0.212	1.318	0.378	0.796	0.317	0.147	0.177	0.393	< 0.001	ANOVA	0.235
TTC Reaction time (*s*)	6.013	3.058	1.476	0.986	0.445	0.306	0.104	0.267	0.015	0.124	0.019	0.171	< 0.001	Friedman	
Min TTC (*s*)	5.268	2.834	0.940	0.431	0.805	0.391	0.350	0.414	0.089	0.039	0.669	0.002	< 0.001	Friedman	
Stop distance to motorcycle (*m*)	21.596	13.892	5.772	3.272	1.604	1.308	0.896	0.157	0.129	0.296	0.002	0.004	< 0.001	Friedman	
Following a slow-driving car															
Mean following distance (*m*)	37.252	41.736	43.858	46.312	1.476	3.386	3.390	3.656	0.977	0.077	0.145	0.959	0.162	ANOVA	0.173
MinFollowing distance (*m*)	31.414	31.660	31.369	31.110	1.628	3.093	3.238	3.667	0.601	0.424	0.405	0.293	0.921	ANOVA	0.575
MaxFollowing distance (*m*)	45.883	51.859	57.571	59.920	1.587	3.935	3.534	3.440	0.279	0.073	0.283	0.514	0.005	ANOVA	0.803
Left-turn gap acceptance decision															
LTGAD (indicator use) (*m*)	78.500	80.000	78.000	75.500	2.643	2.406	2.248	1.983	<.001	0.001	0.005	0.021	0.176	Friedman	
LTGAD (throttle use) (*m*)	82.000	82.500	83.000	79.500	1.864	2.036	1.638	1.846	<.001	<.001	<.001	<.001	0.156	Friedman	
Crossing cyclist															
Detection time (*s*)	0.475	0.400	0.475	0.350	0.125	<.001	0.076	<.001	0.525	0.032	0.010	0.001	0.443	Friedman	
Reaction time (*s*)	0.750	0.625	0.666	0.575	0.200	0.025	0.117	0.075	0.658	0.399	0.753	0.027	0.901	Friedman	
TTC detection time (*s*)	1.294	1.699	1.617	1.968	0.225	0.409	0.096	0.062	0.446	0.271	0.029	0.655	0.392	Friedman	
TTC reaction time (*s*)	1.038	1.496	1.441	1.760	0.301	0.391	0.139	0.006	0.268	0.975	0.259	0.026	0.003	Friedman	
MinTTC (*s*)	0.686	0.904	1.153	1.680	0.277	0.391	0.160	0.040	0.085	0.444	0.334	0.166	< 0.001	ANOVA	0.493
traffic signal switches to yellow															
Detection time (*s*)	0.422	0.352	0.384	0.365	0.020	0.033	0.028	0.030	0.525	0.032	0.010	<.001	---	---	---
Reaction time (*s*)	1.295	0.693	0.677	0.827	0.410	0.067	0.063	0.078	<.001	0.110	0.570	0.004	0.056	Friedman	
Stop-location (*m*)	10.539	13.160	11.723	12.045	0.940	1.165	0.826	1.507	0.722	0.771	0.889	0.672	0.729	ANOVA	0.014

Table 2: Driving parameters were analyzed for the six events that drivers were faced with in the driving simulator, under the four different conditions: regular drive (R), in the presence of a glare source (GS), and in the presence of a glare source while wearing straylight filters type 1 and 2 (SLF1 and SLF2, respectively).

7. ACKNOWLEDGMENTS

The authors extend their gratitude to Mr. Thomas Stieglitz for his programming expertise in helping create the events and for his invaluable assistance throughout the experiments and analyses.

8. REFERENCES

Aarts, L., & van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention*, *38*(2), 215–224. https://doi.org/https://doi.org/10.1016/j.aap.2005.07.004

Adamsons, I., Rubin, G. S., Vitale, S., Taylor, H. R., & Stark, W. J. (1992). The effect of early cataracts on glare and contrast sensitivity: a pilot study. *Archives of Ophthalmology*, *110*(8), 1081–1086.

Ball, K., Owsley, C., Stalvey, B., Roenker, D. L., Sloane, M. E., & Graves, M. (1998). Driving avoidance and functional impairment in older drivers. *Accident Analysis & Prevention*, *30*(3), 313–322.

Breyer, G. (2010). Safe distance between vehicles. *Conference of European Directors of Roads (CEDR)*.

Caird, J. K., Chisholm, S. L., Edwards, C. J., & Creaser, J. I. (2007). The effect of yellow light onset time on older and younger drivers' perception response time (PRT) and intersection behavior. *Transportation Research Part F: Traffic Psychology and Behaviour*, *10*(5), 383–396.

Coeckelbergh, T. R. M., Brouwer, W. H., Cornelissen, F. W., Van Wolffelaar, P., & Kooijman, A. C. (2002). The effect of visual field defects on driving performance: a driving simulator study. *Archives of Ophthalmology*, *120*(11), 1509–1516.

Coppens, J. E., Franssen, L., van Rijn, L. J., & van den Berg, T. J. T. P. (2006). Reliability of the compensation comparison stray-light measurement method. *Journal of Biomedical Optics*, *11*(3), 34027. https://doi.org/10.1117/1.2209555

Cordes, C., Heutink, J., Brookhuis, K. A., Brouwer, W. H., & Melis-Dankers, B. J. M. (2018). Driving slow motorised vehicles with visual impairment—A simulator study. *Cogent Psychology*, *5*(1), 1485473.

Crepeau, E. B., Cohn, E. S., Schell, B. A. B., & Willard, H. S. (2009). Willard & Spackman's occupational therapy. In *Lippincott Williams & Wilkins*.

Cuenen, A., Jongen, E. M. M., Brijs, T., Brijs, K., Houben, K., & Wets, G. (2016). Effect of a working memory training on aspects of cognitive ability and driving ability of older drivers: Merits of an adaptive training over a non-adaptive training. *Transportation Research Part F: Traffic Psychology and Behaviour*, *42*, 15–27.

Čulík, K., Kalašová, A., & Štefancová, V. (2022). Evaluation of driver's reaction time measured in driving simulator. *Sensors*, *22*(9), 3542.

de Wit, G. C., Franssen, L., Coppens, J. E., & van den Berg, T. J. T. P. (2006). Simulating the straylight effects of cataracts. *Journal of Cataract and Refractive Surgery*, *32*(2), 294–300. https://doi.org/10.1016/j.jcrs.2006.01.048

Department for transport. (2014). *Reported Road Casualties Great Britain: 2017 Annual Report*. Department for Transport Statistics. https://bitly.ws/ZyWy

ECOO. (2017). *Visual standards for driving in Europe. A Consensus Paper.* https://www.ecoo.info/wp-content/uploads/2017/01/Visual-Standards-for-Driving-in-Europe-Consensus-Paper-January-2017.pdf

Elliott, D. B., & Situ, P. (1998). Visual acuity versus letter contrast sensitivity in early cataract. *Vision Research*, *38*(13), 2047–2052.

Hayward, J. C. (1972). *Near miss determination through use of a scale of danger*.

Hwang, A. D., Tuccar-Burak, M., Goldstein, R., & Peli, E. (2018). Impact of oncoming headlight glare with cataracts: a pilot study. *Frontiers in Psychology*, *9*, 164.

ISA, I. S. A. (2012). SWOV Fact sheet - Headway times and road safety. *Reproduction*. https://swov.nl/system/files/publication-downloads/fs_headway_archived.pdf

Łabuz, G., Reus, N. J., & van den Berg, T. J. T. P. (2017). Light scattering levels from intraocular lenses extracted from donor eyes. *Journal of Cataract & Refractive Surgery*, *43*(9), 1207–1212.

Łabuz, G., Reus, N. J., & Van Den Berg, T. J. T. P. (2015). Ocular straylight in the normal pseudophakic eye. *Journal of Cataract & Refractive Surgery*, *41*(7), 1406–1415.

Lee, H. C. (2003). The validity of driving simulator to measure on-road driving performance of older drivers. *Transport Engineering in Australia*, *8*(2), 89–100.

Lee, J., & Itoh, M. (2020). Effects of driver compensatory behaviour on risks of critical pedestrian collisions under simulated visual field defects. *PLoS One*, *15*(4), e0231130.

Mangione, C. M., Lee, P. P., Gutierrez, P. R., Spritzer, K., Berry, S., & Hays, R. D. (2001). Development of the 25-item National Eye Institute Visual Function Questionnaire. *Archives of Ophthalmology (Chicago, Ill. : 1960)*, *119*(7), 1050–1058. https://doi.org/10.1001/archopht.119.7.1050

Michael, R., Van Rijn, L. J., Van Den Berg, T. J. T. P., Barraquer, R. I., Grabner, G., Wilhelm, H., Coeckelbergh, T., Emesz, M., Marvan, P., & Nischler, C. (2009). Association of lens opacities, intraocular straylight, contrast sensitivity and visual acuity in European drivers. *Acta Ophthalmologica*, *87*(6), 666–671. https://doi.org/10.1111/j.1755-3768.2008.01326.x

Milleville-Pennel, I., & Marquez, S. (2020). Comparison between elderly and young drivers' performances on a driving simulator and self-assessment of their driving attitudes and mastery. *Accident Analysis & Prevention*, *135*, 105317.

Minderhoud, M. M., & Bovy, P. H. L. (2001). Extended time-to-collision measures for road traffic safety assessment. *Accident Analysis & Prevention*, *33*(1), 89–97.

National Safety Council. (2019). *Defensive Driving Courses - The DDC Instructor and administrative reference guide*.

Owsley, C., & McGwin Jr, G. (1999). Vision impairment and driving. *Survey of Ophthalmology*, *43*(6), 535–550.

Owsley, C., Stalvey, B. T., Wells, J., Sloane, M. E., & McGwin, G. (2001). Visual risk factors for crash involvement in older drivers with cataract. *Archives of Ophthalmology*, *119*(6), 881–887.

Plainis, S., Murray, I. J., & Charman, W. N. (2005). The role of retinal adaptation in night driving. *Optometry and Vision Science*, *82*(8), 682–688.

Ross, V., Jongen, E., Brijs, T., Ruiter, R., Brijs, K., & Wets, G. (2015). The relation between cognitive control and risky driving in young novice drivers. *Applied Neuropsychology: Adult*, *22*(1), 61–72.

Ross, V., Jongen, E. M. M., Brijs, K., Vanroelen, G., Beelen, C., Maltagliati, I., van Beers, M., Ruiter, R. A. C., Brijs, T., & Alhajyaseen, W. (2019). The relation between driving errors and executive functioning in intellectually able young novice drivers with autism. *Transportation Research Part F: Traffic Psychology and Behaviour*, *63*, 38–54.

Rozema, J. J., Coeckelbergh, T., Caals, M., Bila, M., & Tassignon, M.-J. (2013). Retinal Straylight before and after Implantation of the Bag in the Lens IOL. *Investigative Ophthalmology & Visual Science*, *54*(1), 396–401.

Rozema, J. J., Sanchez, V., Artal, N., Gramajo, A. L., Torres, E., Luna, J. D., Iribarren, R., Tassignon, M.-J., & Juarez, C. P. (2015). Lens opacity based modelling of the age-related straylight increase. *Vision Research*, *117*, 25–33. https://doi.org/https://doi.org/10.1016/j.visres.2015.08.017

Rozema, J. J., van den Berg, T. J. T. P., & Tassignon, M. J. (2010). Retinal straylight as a function of age and ocular biometry in healthy eyes. *Investigative Ophthalmology and Visual Science*, *51*(5), 2795–2799. https://doi.org/10.1167/iovs.09-4056

Shechtman, O., Classen, S., Awadzi, K., & Mann, W. (2009). Comparison of driving errors between on-the-road and simulated driving assessment: a validation study. *Traffic Injury Prevention*, *10*(4), 379–385.

Singh, S. (2015). Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. In *National Highway Traffic Safety Administration* (Issue February). https://bitly.ws/Zz33

Svetina, M. (2016). The reaction times of drivers aged 20 to 80 during a divided attention driving. *Traffic Injury Prevention*, *17*(8), 810–814.

Underwood, G., Crundall, D., & Chapman, P. (2011). Driving simulator validation with hazard perception. *Transportation Research Part F: Traffic Psychology and Behaviour*, *14*(6), 435–446.

van Bree, M. C. J., van Verre, H. P., Devreese, M. T., Larminier, F., & van den Berg, T. J. T. P. (2011). Straylight values after refractive surgery: screening for ocular fitness in demanding professions.

Ophthalmology, *118*(5), 945–953.
Van den Berg, T., Franssen, L., & Coppens, J. E. (2010). Ocular media clarity and straylight. *Encyclopedia of the Eye*, 173–183.
Van Den Berg, T. J. (1995). Analysis of intraocular straylight, especially in relation to age. *Optometry and Vision Science: Official Publication of the American Academy of Optometry*, *72*(2), 52–59.
van den Berg, T. J. T. P. (2017). Measurement of straylight for glare assessment and driving. *Scandinavian Journal of Optometry and Visual Science*, *10*, 1–6.
Van Den Berg, T. J. T. P., & Coppens, J. E. (2015). *Method and device for measuring retinal stray light*. Google Patents.
Van den Berg, T. J. T. P., Franssen, L., Kruijt, B., & Coppens, J. E. (2013). History of ocular straylight measurement: A review. *Zeitschrift Fur Medizinische Physik*, *23*(1), 6–20. https://doi.org/10.1016/j.zemedi.2012.10.009
Van Den Berg, T. J. T. P., Van Rijn, L. J. (René., Michael, R., Heine, C., Coeckelbergh, T., Nischler, C., Wilhelm, H., Grabner, G., Emesz, M., Barraquer, R. I., Coppens, J. E., & Franssen, L. (2007). Straylight Effects with Aging and Lens Extraction. *American Journal of Ophthalmology*, *144*(3). https://doi.org/10.1016/j.ajo.2007.05.037
Van Den Berg, T. J. T. P., Van Rijn, L. J. R., Michael, R., Heine, C., Coeckelbergh, T., Nischler, C., Wilhelm, H., Grabner, G., Emesz, M., & Barraquer, R. I. (2007). Straylight effects with aging and lens extraction. *American Journal of Ophthalmology*, *144*(3), 358–363.
Van Der Horst, R., & Hogema, J. (1993). *Time-to-collision and collision avoidance systems*.
van der Meulen, I. J. E., Gjertsen, J., Kruijt, B., Witmer, J. P., Rulo, A., Schlingemann, R. O., & van den Berg, T. J. T. P. (2012). Straylight measurements as an indication for cataract surgery. *Journal of Cataract & Refractive Surgery*, *38*(5), 840–848.
Van Der Meulen, I. J. E., Gjertsen, J., Kruijt, B., Witmer, J. P., Rulo, A., Schlingemann, R. O., & Van Den Berg, T. J. T. P. (2012). Straylight measurements as an indication for cataract surgery. *Journal of Cataract and Refractive Surgery*, *38*(5), 840–848. https://doi.org/10.1016/j.jcrs.2011.11.048
Van Rijn, L. J., Wilhelm, H., Emesz, M., Kaper, R., Heine, S., Nitsch, S., Grabner, G., & Völker-Dieben, H. J. (2002). Relation between perceived driving disability and scores of vision screening tests. *British Journal of Ophthalmology*, *86*(11), 1262–1264.
VIAS. (1998). *De online Referentie van de wegcode*. . https://www.wegcode.be/nl
Ville de hannut. (2018). *Conducteurs éblouis par le soleil: 1 accident tous les 2 jours en Wallonie*. http://bitly.ws/Pro5
Vogel, K. (2003). A comparison of headway and time to collision as safety indicators. *Accident Analysis & Prevention*, *35*(3), 427–433.
Wang, C., Quddus, M. A., & Ison, S. G. (2013). The effect of traffic and road characteristics on road safety: A review and future research direction. *Safety Science*, *57*, 264–275. https://doi.org/https://doi.org/10.1016/j.ssci.2013.02.012
Wotton, E. (2000). The IESNA Lighting Handbook and office lighting. *Lighting*, *14*.