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The effects of simulated acuity and contrast sensitivity impairments on detection of pedestrian hazards in a driving simulator

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Abstract

Driving is a highly visual task, yet the vision requirements for driving licensure vary widely. All US states have a threshold for visual acuity (e.g. most use 20/40 for an unrestricted license). Contrast sensitivity (CS) is not measured for licensure, despite evidence that it may be a better predictor of crash risk than visual acuity (VA). Two experiments were conducted to investigate how simulated reductions in VA and CS affect the detection of pedestrians in a driving simulator during the daytime in a highway setting. Young normally-sighted current drivers wore goggles simulating different levels of VA and CS loss (within a range that would meet licensing criteria) and pressed the horn as soon as they saw a pedestrian. The proportion of pedestrians detected and driving speed was not different between the conditions. Reducing VA alone did not significantly reduce reaction time or the deceleration needed to stop before the collision point. However, adding a CS loss to a VA deficit increased both reaction time and the deceleration required to stop before the collision point. These results suggest that an individual's CS should be considered when determining visual fitness to drive, especially in the early stages of ocular disease, such as cataract, where CS may be impaired while high contrast VA is still relatively unimpaired.

Keywords

hazard detection; simulated vision impairment; driving simulation

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Author contributions
All authors contributed to the writing and editing of the data. The study concept was developed by A.B. and G.S. Data collection and data processing was conducted by G.S., J.A., J.H., and M.S. The programming and data analysis was performed by G.S. All authors approved the final version of the manuscript for submission.

1. Introduction

The ability to drive safely may be affected by a driver's visual status (Owsley & McGwin, 2010). In the US, regulations regarding the visual requirements of drivers to obtain or renew a driver's license are determined individually by state and based predominantly on a visual acuity (VA) screening test. The majority of states require VA of at least 20/40 in the better eye for an unrestricted, non-commercial driver's license with a handful of states allowing a VA up to 20/70 (Peli, 2008). If the VA standard is not met for an unrestricted license, drivers may still be able to obtain a restricted license that requires certain limitations (e.g. no nighttime driving) with a VA typically up to 20/100, or 20/200 in a few states (Peli, 2008). However, some eye diseases reduce aspects of vision that may be important for driving while VA is still within the standards for licensure.

Contrast sensitivity (CS) is one aspect of vision that is not measured for licensure in any state, yet CS can be reduced by cataracts, glaucoma, macular degeneration, and other eye diseases. For many years, CS has been investigated as being highly relevant to driving (Ginsburg, 1987; Shinar & Schieber, 1991). In one study, drivers with a history of crash involvement were found to be 6 times more likely to have reduced CS levels compared to drivers without a history of crash involvement (Owsley, Stalvey, Wells, Sloane, & McGwin, 2001). Furthermore, drivers were found to have reduced crash risk (Owsley et al., 2002) and to have better driving performance (Wood & Carberry, 2006) following cataract surgery, with improvement in CS being the best predictor of improved driving ability (Wood & Carberry, 2006). Though severe CS deficits have been associated with individuals reducing or ceasing driving (e.g. Freeman, Munoz, Turano, & West, 2005), individuals with mild CS deficits may not modify their driving frequency and may meet the minimum legal VA standards for driving in their state. The experiments in this paper utilized simulated visual impairment to evaluate the effects of mild-to-moderate simulated VA and CS loss on pedestrian detection in a high-fidelity driving simulator.

Simulating vision impairment has the advantage of homogenizing specific vision deficits across a sample of participants, which is often impossible with real vision impairment. A number of studies using closed-course driving tracks (Higgins, Wood, & Tait, 1998; Higgins & Wood, 2005) and driving simulators (Brooks, Tyrrell, & Frank, 2005) have utilized positive spherical lenses that produce optical blur to reduce VA in normal vision participants. These studies found that, in daytime conditions, simulated VA deficits decreased the number of correctly read signs (Higgins, Wood, & Tait, 1998; Higgins & Wood, 2005) and reduced detection of stationary objects, such as low-contrast road hazards (Higgins, Wood, & Tait, 1998; Higgins & Wood, 2005) or pedestrians (Brooks, Tyrrell, & Frank, 2005). Many of these findings were most pronounced when VA was worse than or equal to 20/100. By comparison, even mild reductions in VA (20/40) were found to reduce pedestrian recognition distances in nighttime driving (Wood et al., 2012; Wood, Marsalek, Carberry, Lacherez, & Collins, 2015).

Researchers simulating cataracts have typically used frosted lenses (Wood & Troutbeck, 1994) or diffusing filters (e.g. Bangerter filters: Lehsing et al., 2019) to reduce both VA and CS in normal vision participants. Similar to the results of simulated VA loss, the simulation of cataracts decreased the number of signs correctly read (Higgins & Wood, 2005; Wood, Chaparro, & Hickson, 2009; Wood & Troutbeck, 1994) and increased collisions with low-contrast road hazards (Higgins & Wood, 2005) in closed-course driving tracks. In the driving simulator, mild simulated reductions in CS and VA significantly delayed time to first fixate on crossing pedestrians, but did not impact driving safety (Lehsing et al., 2019). Importantly, in each of these studies, VA with the simulated cataracts was within or near legal limits for an unrestricted license (i.e. around 20/40). When compared to a simulation of VA reduction alone, one study found that the simulated cataracts (combined VA and CS impairment) reduced performance to the same level as a reduction of VA to 20/200 (Higgins & Wood, 2005). Thus, these studies suggest that even minor reductions in CS may have implications for detecting hazards while driving.

The present studies aimed to expand the previous literature by 1) parametrically manipulating a gradation of simulated deficits of both CS and VA, 2) evaluating their effects on reaction times to potential pedestrian hazards, and 3) determining what deceleration rate would be required to stop prior to a collision based on the reaction time and speed of the car. For example, if a driver slows down to compensate for their vision impairment, an increased reaction time may not represent the same level of collision risk as would be the case if the driver never altered their speed. Thus, determining the safety of the response by measuring the degree of deceleration required to avoid the collision seems critical in evaluating the effects of changes in VA and CS on hazard detection when driving. Using the safe, controlled environment of a driving simulator, two experiments were conducted. In the first experiment increasingly stronger (denser) diffusing filters (Bangerter filters), which reduced both CS and VA (Odell, Leske, Hatt, Adams, & Holmes, 2008), were used to test the hypothesis that graded reductions in CS and VA would have increasing effects on reaction time and the deceleration needed to avoid a collision. The second experiment concentrated on testing the hypothesis that CS deficits would have greater effects on pedestrian detection than VA deficits by comparing hazard detection while wearing the diffusing filters to hazard detection while wearing sphere lenses that reduced VA to the same level as the diffusing filters but did not significantly impair CS.

2. Experiment 1 - Materials and Methods

In the first experiment, participants wore goggles fitted with filters that created different levels of simulated visual impairment while driving in a simulator to determine the combined effects of VA and CS reductions on pedestrian detection. Filters of increasing density were used to simulate three levels of VA loss: a mild VA loss at about 20/25, which is within the legal requirements for an unrestricted license in Massachusetts (MA); a mild VA loss at about 20/40, which is just at the borderline of the requirements for an unrestricted license in MA; and a moderate VA loss at about 20/80, which is within the range of a restricted license in MA. The simulated CS losses were within the range of CS measured in individuals with cataracts whose VA was 20/80 or better and had no other ocular abnormalities (Rubin, Adamsons, & Stark, 1993).

2.1. Participants

Participants included fifteen young adults (6 male, mean age = 26.9 years, st. d. age = 4.3). All participants were current drivers with at least 2 years driving experience that met the current vision requirements for driving in MA (at least 20/40 binocular VA) and self-reported no adverse history of ocular disease. Participants wore their habitual correction of glasses or contact lenses if necessary. All participants were instructed that they would be driving in a driving simulator with simulated visual impairment and all participants read and signed an informed written consent prior to beginning the experiment. The study followed the tenets of the Declaration of Helsinki and was approved by the institutional review board at the Schepens Eye Research Institute.

2.2. Simulations of reduced VA and reduced CS

There were 4 conditions used in the current analyses. In the normal vision (*NV*) condition, the participant was tested with his/her normal vision and habitual glasses if routinely used. For each of the three simulated vision impairment conditions, Bangerter diffusing filters (Fresnel Prism & Lens Co., Eden Prairie, MN) were attached to the outer surface of clear-lens safety goggles that fitted over the habitual glasses (if worn) and did not restrict the driver's field of view. There were three sets of goggles, one for each condition. All participants used the same set of goggles. In the *Low* filter condition, 0.4 opacity filters were attached to the lenses; in the *Mid* filter condition 0.1 opacity filters were attached; while in the *High* filter condition the 0.4 and 0.1 filters were both used (one attached on the inner surface and one on the outer surface of the goggle lenses). In addition, a 5th condition (equivalent to Mid_{DS} in Experiment 2) was used to provide pilot data in preparation for Experiment 2. Data from this 5th condition are not included in analyses for Experiment 1 because the condition was replicated in Experiment 2 (see Appendix A1.1).

Binocular VA for all conditions was measured prior to the driving assessment at 100 cm, which is approximately equivalent to the viewing distance in the driving simulator, with Test Chart 2000 Pro software (Thomson Software Solutions; Hatfield, Hertfordshire, UK). Binocular contrast sensitivity for letters was measured at 50cm using a Mars chart (Mars Perceptrix; Chappaqua, NY), which contained rows and columns of letters (2° vertical subtense) of decreasing contrast.

2.3. Apparatus

The driving simulator (LE-1500; FAAC Corp., Ann Arbor, MI) consisted of five 42-inch LCD monitors (LG M4212C-BA, native resolution of 1366 × 768 pixels), which provided a 225° horizontal field of view. The central screen (64° horizontal, 32° vertical) provided the view through the windshield while the flanking and lateral screens provided the view from the lateral windows. The back- and side- view mirrors were inset on the LCD monitors simulating the position in a real car (top image Figure 1). A dashboard displaying the speed and a clock was displayed at the bottom of the central screen. The controls and dashboard of the simulator resembled a fully automatic Ford Crown-Victoria. Participants were seated in a motion based seat, which had 3 degrees of freedom in its movement to simulate the motion of a car seat when accelerating, decelerating, and driving over different terrains. Data from the simulator were collected at 30Hz and included the location, speed, and status of all programmed objects in addition to the participant's vehicle.

2.4. Driving scenarios and pedestrian events

The virtual world was developed using the Scenario Development Toolbox by FAAC Corp (FAAC Corp., Ann Arbor, MI) and contained a rural two-lane highway (100kph; one lane in each direction) with scenery predominately being green hills and trees. The simulated highway included long curves and inclines with oncoming traffic programmed on the lane opposite of the driver as used in prior driving simulator studies (e.g. Bronstad, Bowers, Albu, Goldstein, & Peli, 2013; Alberti, Peli, & Bowers, 2014). Four routes were developed, each starting at a different location along the highway. Twelve pedestrian models were scripted to appear at pseudorandom intervals along each route with at most 60s between appearances when driving at the 100kph speed limit. Each pedestrian was triggered to appear when the participant’s vehicle was 134m away, equivalent to 5s when travelling at 100kph, providing sufficient time to respond and avoid a collision. Pedestrian models were 2m tall and were outfitted with a white shirt and blue trousers (bottom row Figure 1). They could appear at eccentricities of about 4° (e.g. adjacent lane/sidewalk) and 14° (e.g. further than adjacent lane/sidewalk) on the right and left of the roadway relative to the heading direction of the car with equal numbers on the right and left. After appearing, pedestrians who appeared at 14° ran (11-13kph) and those who appeared at 4° walked briskly (4-7kph) towards the road as if to cross in front of the participant’s vehicle. The pedestrians moved at these speeds to ensure they were on a collision course (constant bearing angle) with the driver when driving at or close to the speed limit. Pedestrians stopped before a collision occurred to prevent any distress that might be experienced if the driver collided with the pedestrian.

2.5. Procedure

Prior to the experimental drives, participants completed two practice drives. The first practice drive (5 - 10 minutes) was used to acclimatize the participant to controlling the vehicle on an empty highway. The second practice drive (about 10 minutes) included all the elements (pedestrian events and other traffic) of the test drives. The participant’s task was to press the horn as soon as a pedestrian appeared while driving. In the second half of the second practice drive, participants wore the *Mid* filter condition goggles to become familiar with driving with simulated vision impairment. Once participants felt comfortable operating the simulated vehicle and understood the instructions of the task, they began the experimental drives (each 8–10 minutes) with short breaks between. There was one drive for each of the four conditions (*NV, Low, Mid,* and *High*) with the order of the simulated goggles and starting section of the highway pseudorandomized across participants. There were no significant effects of testing order (see Appendix A1.2 for analyses).

In addition to pressing the horn as soon as they detected a pedestrian, participants were instructed to drive as they would do in real life situations and to obey all the normal rules of the road. A speed cap of 100kph was set and participants were encouraged to stay at or as close to the speed limit as possible while maintaining good control of vehicle steering.

2.6. Detection performance measures

Four dependent measures were used to quantify detection performance: detection rate (the percentage of pedestrians detected), reaction time (the time between when the pedestrian appeared in the scene and the time of the horn press), car speed at the time of the horn press, and the deceleration (m/s^2) required to stop before the collision point, which is indicative of the safety of the detection. The deceleration was computed with the following formula:

$$\text{deceleration} = \frac{V_f^2 - V_h^2}{2D_h}$$

Where V_f is the final velocity that was fixed to be 0, V_h is the velocity at the time of the horn press, and D_h is the distance to the collision point at the time of the horn press. The collision point was defined as the location where the front of the car would intersect with the pedestrian assuming the pedestrian continued on its trajectory and did not stop before a collision.

2.7. Statistical analyses

First, the effects of diffusing filter (*NV, Low, Mid,* and *High*) on CS and VA were evaluated with a repeated measures analysis of variance (ANOVA), and then followed with paired t-tests to determine whether there were significant reductions in CS and VA between successive conditions.

Second, the effects of diffusing filter on car speed were examined. The speed of the car at the time of the horn press was on average greater than 90kph across all conditions (indicating that participants were following the instructions to maintain a speed near 100kph) and not significantly different between conditions in a Kruskall-Wallis Test [χ^2 (3) = 0.3, p = 0.96]. Thus, the speed of the car at the time of the horn press was not analyzed any further.

Finally, the effects of diffusing filter on detection performance were evaluated. Average detection rates were high (above 95%) and did not differ across conditions (Kruskall-Wallis Test [χ^2 (3) = 4.3, p = 0.23]). Therefore, detection rates were not analyzed any further. For the continuous outcome variables, reaction time and deceleration, linear mixed models (LMM) were constructed in MATLAB (*fitglme.m*: Mathworks, R2015a). Main effects were evaluated by entering the conditions as different levels (*NV* = 1, *Low* = 2, *Mid* = 3, *High* = 4) and simple effects were evaluated by defining the different levels categorically (e.g. *NV, Low, Mid, High*) and dummy coding the reference level (e.g. *Low* was used as the reference level when comparing *NV* to *Low* and *Low* to *Mid*). A random effects structure was used for participant number to account for individual differences between participants and for pedestrian event to account for variance between different pedestrian events between the different scenarios. Both random effects structures included random slopes and intercepts for all fixed effects and their interactions to produce a maximal random effects structure (Barr et al., 2013). All of the maximal models converged.

Pedestrian events with a reaction time that exceeded 3 standard deviations above the mean were excluded from analyses (23 total). After excluding the outlier reaction times, reaction time was normalized using log10 given that reaction time data were positively skewed (Ratcliff, 1993), resulting in 697 total events used for analyses.

3. Experiment 1 - Results

3.1. CS and VA levels across different conditions

As the strength of the diffusing filter increased, the amount of VA [F(4,14) = 112.3, p < 0.001] and CS [F(4,14) = 84.1, p < 0.001] impairment significantly increased (Figure 2). VA was significantly worse when comparing *Low to NV* [t(14) = 8.2, p < 0.001], *Mid* to *Low* [t(14) = 4.1,p < .002], and *High* to *Mid* [t(14) = 7.8, p < 0.001]. Additionally, CS was significantly worse when comparing *Low to NV* [t(14) = 7.9, p < 0.001], *Mid* to *Low* [t(14) = 4.2, p < 0.001], and *High* to *Mid* [t(14) = 4.8, p < 0.001]. See Table 1 for more details.

3.2. Detection performance across different conditions

Reaction time across the different conditions is displayed in Figure 3 (top row). There was a significant main effect of condition on reaction time [β = 0.046, se = 0.007, t = 6.99, p < 0.001]. Reaction time significantly increased from *NV* to *Low* [β = 0.033, se = 0.013, t = 2.57, p = .01], *Low* to *Mid* [β = 0.062, se = 0.016, t = 3.87, p < 0.001] and *Mid* to *High* [β = 0.035, se = 0.016, t = 2.12, p =.034]. These results suggest that decreased VA and CS as a function of increased filter strength increased the time needed to respond to potential hazards.

The deceleration needed to stop prior to the collision point across the different conditions is displayed in Figure 3 (bottom row). There was a significant main effect of condition on deceleration [β = 0.26, se = 0.073, t = 3.52, p < 0.001]. The deceleration increased significantly (became less safe) from *Low* to *Mid* [β = 0.41, se = 0.14, t = 2.96, p < .005] and from *Low* to *High* [β = 0.77, se = 0.26, t = 2.96, p < .005], but there was no significant difference between *NV* and *Low* [β = 0.02, se = 0.1, t = 0.19, p = 0.85] and between *Mid* and *High* [β = 0.36, se = 0.22, t =1.68, p = 0.094]. Similar to reaction time, as the strength of the filter increased, so did the deceleration needed to stop before the collision point.

4. Experiment 2 - Materials and Methods

In Experiment 1, increasing the strength of the filters significantly affected both the reaction time and deceleration needed to stop prior to the collision point, suggesting that reductions in both VA and CS influenced the participants' ability to safely detect hazards. However, Experiment 1 did not indicate whether it was the reduction in VA, CS, or in both that negatively affected detection performance. The goal of Experiment 2 was to investigate how changes in VA and CS each impact detection performance.

4.1. Participants

Sixteen new participants were recruited for Experiment 2. One participant was excluded for not having sufficiently matched sphere lenses (explained below), resulting in 15 total participants (12 males, mean age = 31.3 years, st.d. age = 10). The criteria for selecting participants were the same as Experiment 1.

4.2. Simulations of reduced VA and reduced CS

Five conditions were used in Experiment 2: the *NV* condition, two of the filter conditions from Experiment 2 (*Mid* filter and *High* filter) and two additional conditions in which positive spherical lenses were used to reduce VA while leaving CS relatively unchanged (similar to individuals with myopia driving without a spectacle prescription). In the Mid_{DS} condition, participants wore lenses that reduced VA to the level of the *Mid* filter condition. In the $High_{DS}$ condition, participants wore lenses that reduced VA to the level of the *High* filter condition.

4.3. Procedure

First the power of the sphere lens for the Mid_{DS} and $High_{DS}$ conditions was determined individually for each participant at a 100 cm test distance (similar to the viewing distance in the driving simulator). First, VA was recorded for the *Mid* and *High* filters. Then, VA was recorded for sphere lenses that were clipped on over plano spectacles or on the participant's own spectacles. The sphere lenses ranged from +1.00 DS to +4.00 DS in steps of 0.50 DS. The sphere lens for which the VA was within 1 line (0.1 logMAR) of the *Mid* filter VA was selected as the sphere lens for the Mid_{DS} condition. The sphere lens for which the VA was within 1 line (0.1 logMAR) of the *High* filter VA was selected as the sphere lens for the $High_{DS}$ condition.

All other procedures for Experiment 2 were the same as for Experiment 1. Participants drove in the same driving simulator, used the same *Mid* and *High* filter goggles, and completed the same pedestrian detection task with one drive per condition. The order of the drives was pseudorandomized across participants. There were no significant effects of test order on detection performance measures (see Appendix A1.2).

4.4. Statistical Analysis

First, the effects of the different conditions on VA and CS were evaluated. Paired t-tests were used to quantify differences in VA and CS between pre-specified pairs of conditions, as detailed in the results.

Next the effects of the different conditions on car speed were examined. As in Experiment 1, average speeds were at least 90kph, did not differ significantly across conditions [χ^2 (4) = 0.79, p = 0.94], and therefore, were not analyzed further.

Finally, the effects of the different conditions on detection performance were evaluated. Again, detection rates were high (at least 90%) in all conditions, did not differ significantly across conditions [χ^2 (4) = 1.0, p = 0.90], and therefore, were analyzed any further. Two LMMs were created to evaluate the effects that CS and VA reductions had on reaction times and deceleration; the first included the conditions *NV*, Mid_{DS}, and *Mid* to evaluate the effects of the mid-level VA and CS reductions, while the second included *NV*, $High_{DS}$, and *High* to evaluate the effects of the high-level VA and CS reductions (see results for more detail). As in Experiment 1, main effects were evaluated by treating the conditions as different levels (e.g. *NV* = 1, Mid_{DS} = 2, *Mid* = 3) and simple effects were evaluated by treating the levels as categorical and dummy coding the reference level. As in Experiment 1, all maximal models converged.

To evaluate the interaction between CS and VA reductions on reaction time and deceleration, additional LMMs were constructed with Mid_{DS} coded as 'CS=0,VA=0', *Mid* coded as 'CS=1, VA=0', $High_{DS}$ coded as 'CS=0,VA=1', and *High* coded as 'CS=1,VA=1'. The version of this model that contained an interaction between CS and VA was compared to a version without the interaction using a likelihood ratio test (*compare.m*: Mathworks, R2015a) to determine the significance of the interaction.

Outliers were removed using the same procedure as in Experiment 1. After outlier exclusion (21 events), there were a total of 879 events used in the analyses.

In addition to the main analyses for Experiment 2 reported below, we repeated the analyses from Experiment 1 in which the effects of each of the diffusing filters (*Mid* and *High*) was compared to *NV* and verified that the Experiment 1 results were replicated in a different sample (see Appendix A1.3).

5. Experiment 2 – Results

5.1. CS and VA levels across different conditions

As can be seen in Figure 4, VA was significantly reduced when comparing *NV* to Mid_{DS} [t(14) = 10.5, p < 0.001] and when comparing *NV* to $High_{DS}$ [t(14) = 18.3, p < 0.001], but importantly, the CS was not significantly different when comparing *NV* to Mid_{DS} [t(14) = 0.63, p = 0.54] and when comparing *NV* to $High_{DS}$ [t(14) = 1.5, p = 0.16]. Thus the effects of a VA difference alone on driving could be investigated by comparing Mid_{DS} and $High_{DS}$ to *NV* given that the only difference between these conditions was the reduced VA in the Mid_{DS} and $High_{DS}$ conditions relative to *NV*.

When comparing Mid_{DS} and $High_{DS}$ to *Mid* and *High*-filter conditions, respectively, the reverse results were found. That is, CS was significantly reduced when comparing Mid_{DS} to *Mid* [t(14) = 10.7, p < 0.001] and $High_{DS}$ to *High* [t(14) = 18.1, p < 0.001], but VA was not significantly different between Mid_{DS} and *Mid* [t(14) = 0.06, p = 0.95] nor between $High_{DS}$ and *High* [t(14) = 2.06, p = 0.06]. The effects of adding a CS deficit to a VA loss could therefore be explored by comparing Mid_{DS} and $High_{DS}$ to *Mid* and *High* respectively, given the large differences in CS but the similarity in VA between these conditions. See Table 2 for more details.

5.2. Effects of mid-level CS and VA reduction (*NV*, Mid_{DS}, & *Mid*)

Consistent with the results of Experiment 1, when both VA and CS were reduced from *NV* to *Mid* (left column Figure 5), there was a significant increase in reaction time [β = 0.08, se = 0.023, t = 3.34, p < 0.001] and a significant increase in deceleration [β = 0.57, se = 0.16, t = 3.56, p < 0.001].

When comparing *NV* to Mid_{DS} to determine the effect that a reduction in VA alone had on detection performance, there was no significant increase in reaction time [β = 0.003, se = 0.019, t = 0.18, p = 0.86] nor increase in deceleration [β = 0.04, se = 0.11, t = 0.35, p = 0.73]. However, when comparing Mid_{DS} to *Mid,* to determine the effect of adding a reduction in CS to a VA deficit, there was a significant increase in reaction time [β = 0.076, se = 0.017, t = 4.51, p < 0.001] and increase in deceleration [β = 0.61, se = 0.14, t = 4.33, p < 0.001]. Taken together, these results suggest that a VA deficit alone (around the level of 20/40) neither increased reaction time nor deceleration needed to stop prior to the collision, but pairing that VA deficit with a CS deficit did negatively affect detection performance with the CS deficit being the primary cause of the poorer detection performance.

5.3. Effects of high-level CS and VA reduction (*NV, High*$_{DS}$, and *High*)

Consistent with the results of Experiment 1, when both VA and CS were reduced from *NV* to *High* (right column Figure 5), there was a significant increase in reaction time [β = 0.12, se = 0.027, t = 4.54, p < 0.001] and increase in deceleration [β = 0.62, se = 0.2, t = 3.11, p < .005].

When comparing *NV* to $High_{DS}$ to determine the effect that a reduction in VA alone had on detection performance, there was a non-significant, though trending, increase in reaction time [β = 0.04, se = 0.021, t = 1.94, p = 0.053] but no significant increase in deceleration [β = 0.19, se = 0.14, t = 1.4, p = 0.16]. When comparing $High_{DS}$ to *High* to determine the effects of adding a reduction in CS to a VA deficit, there was a significant increase in reaction time [β = 0.08, se = 0.022, t = 3.66, p < 0.001] and a significant increase in deceleration [β = 0.42, se = 0.18, t = 2.4, p = 0.017]. These results again suggest that a VA deficit alone (around the level of 20/80) did not significantly affect detection performance, but the combined deficit in VA and CS did negatively affect detection.

5.4. Interaction between CS and VA

The interaction between a CS and VA reduction was evaluated to determine their effects when combined on reaction time and deceleration. There was no significant interaction of CS and VA on reaction time [χ^2 (1) = 0.11, p = 0.74] nor deceleration [χ^2 (1) = 1.21, p = 0.27]. The non-significant interactions were likely the result of the average differences between Mid_{DS} and *Mid* (reaction time = 1.2s, deceleration = 0.6m/s^2) being similar to the average differences between $High_{DS}$ and *High* (reaction time = 1.2s, deceleration = 0.5m/s^2).

5.5. Combined analyses of Experiment 1 and Experiment 2

To determine whether CS, VA, or a combination of CS and VA best predicted reaction time and deceleration, model comparison was used to compare 4 regression models that used data from both experiments with the following combinations of predictors; 1) VA alone, 2) CS alone, 3) VA and CS, and 4) VA, CS, and the interaction between VA and CS. The Bayesian information criterion (BIC) was compared between the different models to account for the additional complexity of the VA and CS model and the VA, CS, and interaction model with differences above 6 indicating strong evidence against the model with the higher BIC (Kass & Raftery, 1995). For reaction time, the CS alone model had a substantially lower BIC

(−293.2) than the VA alone model (−277.9), replicating the findings from above that CS more strongly predicts reaction time than VA. However, the CS alone model was not noticeably different from the VA and CS model (−297) and VA, CS, and interaction model (−292.5), given that the difference in BIC of each model was within about 4 units. With regards to deceleration, similar results were found; the CS alone model (262.3) had a lower BIC than the VA alone model (274.4), but was not different from the VA and CS model (264.9) and the VA, CS, and interaction model (265.6). Thus, across both experiments, reductions in CS predicted reaction time and deceleration needed to stop before the collision point better than reductions in VA.

6. General Discussion

Driving is a visual task and the quality of the driver's functional vision may influence the safety of the driver (Owsley & McGwin, 2010). Determining which aspects of vision are important for driving safety has important implications for public health. In two experiments, the effects of simulated VA and CS reductions together (Experiment 1) and alone (Experiment 2) were explored to determine how quickly drivers responded to pedestrian hazard s and how safe those detections were in a high-fidelity driving simulator. In both experiments, the amount of simulated VA reduction was selected to be on average within legal limits for either an unrestricted or a restricted license in all conditions.

In Experiment 1, simulated VA and CS deficits using diffusing filters had little effect, if any, on detection rates but significantly increased the reaction time to detecting the hazard and the deceleration required to stop the car before a collision. These results are consistent with the literature that has found slower reaction times with simulated loss in VA and CS for hazards in closed-course driving (Higgins & Wood, 2005) and when viewing clips from a hazard perception test (Marrington, Horswill, & Wood, 2008).

In Experiment 2, sphere lenses (Mid_{DS} and $High_{DS}$) that were VA matched to the diffusing filters (*Mid* and *High*) were used to determine what effect adding a CS loss to a VA deficit had on detection performance. The effects of VA reductions were evaluated by comparing detection performance in the *NV* condition to the conditions when participants wore sphere lenses, which reduced VA relative to *NV* but not CS. The VA loss alone (either about 20/40 or 20/80) did not significantly impair reaction time or deceleration. One potential reason why VA did not significantly affect detection performance was that the pedestrians were highly salient. By comparison, previous studies using similar levels of simulated VA loss found an increase in the number of collisions with low-contrast (grey foam) hazards in a closed-road driving course (e.g. Higgins & Wood, 2005).

The effects of adding the CS loss to the VA deficit were evaluated by comparing performance with the sphere lenses (Mid_{DS} and $High_{DS}$) to the conditions when participants wore the diffusing filters (*Mid* and *High*), given that the conditions had similar levels of VA but the sphere lenses did not reduce CS. There was a significant increase in reaction time and deceleration as a result of the additional CS loss, which was replicated in Experiment 1 (see Appendix A1.1). These results are consistent with a prior study on the effects of simulated VA and CS reductions on hazard detection in a closed-road driving course

(Higgins & Wood, 2005). When looking at the main effects of a VA or CS reduction on detection performance, only the CS reduction significantly affected reaction time and deceleration. Interestingly, the interaction between VA and CS was non-significant, which suggests that the decrements in detection performance in the *Mid* and *High* conditions were primarily due to the CS reduction.

When combining data from both experiments to examine the relationship between VA and CS and detection performance, the regression model of CS alone predicted reaction time and deceleration better than the VA alone model. Previous experiments that have found adverse effects of simulated VA impairments alone on detection performance have used low-contrast hazards and have found the greatest drop offs in performance when VA was at the very extreme of legal limits for a restricted license (e.g. 20/100 and 20/200, Higgins, Wood, & Tait, 1998). Here, we have demonstrated that even in ideal conditions for hazard detection (i.e. clear weather, light traffic, high contrast hazards), mild to moderate reductions in CS produced decrements in hazard detection despite having a VA that would still be within legal limits for at least a restricted license.

In these studies, deceleration required to stop before a collision was used to indicate the safety of the detection, given that it takes into account the speed of the driver at the time of the detection. This measure of safety is similar to deceleration to safety time (DST), which is the deceleration rate required to allow a specific safety margin (in seconds) between the time the first road user (i.e. pedestrian) leaves the collision zone and the second road user (i.e. the driver) enters the collision zone (Hupfer, 1997). Deceleration calculated here is similar to DST with a safety margin of 0s, though in the experiments conducted here, the first road user (i.e. pedestrian) did not actually enter the collision zone. Estimates of what is considered a “safe” deceleration using DST vary between 4 m/s^2 (Hupfer, 1997) or 5 m/s^2 (Evans, 2004). Even using a conservative estimate of 5 m/s^2, the average proportion of unsafe events were high in Experiment 1 (*NV* = 7%, *Low* = 4%, *Mid* = 16%, and *High* 27%) and in Experiment 2 (*NV* = 6%, Mid_{DS} = 7%, $High_{DS}$ = 9%, *Mid* = 17%, *High* = 18%), despite conditions being ideal for hazard detection. In real world driving, there are many factors that could affect hazard detection. For example, when driving at night even small simulated reductions in VA impaired the ability of normally-sighted drivers to detect pedestrians (Wood, Chaparro, Carberry, & Chu, 2010; Wood et al., 2012). Older adults, who typically experience losses in VA and CS from eye diseases such as cataracts (Klein, Klein, & Linton, 1992), were found to be worse at detecting hazards in a hazard perception test than younger adults (Horswill et al., 2008; Scialfa, Deschênes, Ference, & Boone, 2012). It is therefore likely that our findings in the current experiments underestimate the effects of a CS and VA reduction on hazard detection in the real world.

Our results with simulated VA and CS impairment are consistent with results from experiments using individuals with real vision impairment. For example, individuals with central vision loss (mostly from age-related macular degeneration) had slower reaction times and more unsafe detections than normally sighted controls in driving simulator experiments with similar pedestrian hazards (Bronstad, Bowers, Albu, Goldstein, & Peli, 2013; Alberti, Horowitz, Bronstad, & Bowers, 2014; Bronstad, Albu, Bowers, Goldstein, & Peli, 2015). Furthermore, these studies found that CS was a stronger predictor of detection performance than VA (Bronstad et al., 2013; Alberti et al., 2014), which corroborates the results found in the experiments conducted here. On closed course tracks, individuals with vision impairments (mostly bilateral cataracts) had worse sign and low-contrast hazard recognition and hit more of the low-contrast hazards than normally sighted controls (Wood & Carberry, 2006; Wood, 2002; Wood & Carberry, 2004). After cataract surgery, improvement in detection performance was best predicted by improvement in CS (Wood & Carberry, 2006). Taken together, the results of the current experiments with simulated vision loss and those from drivers with real vision loss, suggest that CS, as well as VA, should be assessed when measuring vision for driving licensure. This is especially true of individuals with eye diseases that affect both VA and CS, such as cataracts. In some cases, the VA may be within legal limits despite CS impairment. Measuring CS can be achieved quickly (e.g. Pelli & Bex, 2013), but future research should be directed towards how to efficiently and effectively measure CS in non-clinical or non-laboratory settings.

One potential caveat to this study with regards to its generalizability is that most participants in these experiments drove near the maximum speed. Driving at the maximum speed was an important component of the instructions by the experimenter given that driving below the speed limit, or if no speed cap was used at all, may have resulted in the pedestrians not being on a collision course and therefore not hazardous. However, older drivers and drivers with vision impairments have been found to compensate for their visual deficits by reducing their speed or ceasing driving (e.g. Freeman, Munoz, Turano, & West, 2005; Keefe, Weih, McCarty, & Taylor, 2002). Similarly, older individuals with reduced CS typically cease nighttime driving to compensate as reported in questionnaires (Puell, Palomo, Sanchez-Ramos, & Villena, 2004). Reduced speed was also found for simulated VA and CS impairments in normal vision subjects on a 3km closed road course (Owens, Wood, & Carberry, 2010). It is likely that if participants had been free to drive at their own pace, participants may have reduced their driving speed to compensate for their simulated vision impairment and thus potentially made relatively safer detections.

7. Conclusions

In two experiments using a high-fidelity driving simulator, we found that simulated reductions in CS and VA impaired reaction times to pedestrian hazards and increased the deceleration that would have been required to stop prior to the collision point. CS was found to be a better predictor of the increase in response time and deceleration than VA, which replicates previous findings from the literature. In contrast to the effects of the combined CS and VA impairments, deficits in VA alone (at the level of about 20/40 and 20/80) had little effect on detection performance. These results demonstrate the necessity for measuring CS, along with VA, when assessing whether an individual should receive a driving license.

Acknowledgements

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A1.: Appendix

A1.1 Experiment 1 – Effects of mid-level CS and VA reduction (***NV, Mid_{DS}*, & *Mid***)

In Experiment 1, in addition to *NV, Low, Mid,* and *High,* a Mid_{DS} condition was included to provide preliminary data about the effects of a VA reduction alone compared to a combined VA and CS reduction (*Mid*) on detection performance. As in Experiment 2, the Mid_{DS} condition involved driving with a diopter positive sphere lens that reduced VA to the same level as the *Mid* condition, which was determined prior to driving in the driving simulator. The average car speed (average 91.7kph, sem 1.87kph) and detection rates (average 0.99, sem 0.01) were not significantly different from the average speed [χ^2 (4) = 0.52, p = 0.97] and detection rate [χ^2 (4) = 4.58, p = 0.33] in the other conditions using a Kruskal-Wallis Test. In Experiment 2, we found that the $Mid_{DS/}$ condition, which significantly reduced VA but not CS, only minimally affected detection performance compared to *NV.* Here we conducted the same analyses as in Experiment 2 to determine if those results replicated.

Figure A1.1 displays VA and CS for the different conditions. There was a significant reduction in VA when comparing *NV* to Mid_{DS} [t(14) = 15.3, p < 0.001], but no significant difference when comparing Mid_{DS} to *Mid* [t(14) = 0.24, p = 0.81]. On the other hand, there was no significant reduction in CS when comparing *NV* to Mid_{DS} [t(14) = 1.94, p = 0.07], but a significant reduction when comparing Mid_{DS} to *Mid* [t(14) = 9.6, p < 0.001]. These results replicated the reductions in VA and CS found in the Mid_{DS} condition from Experiment 2.

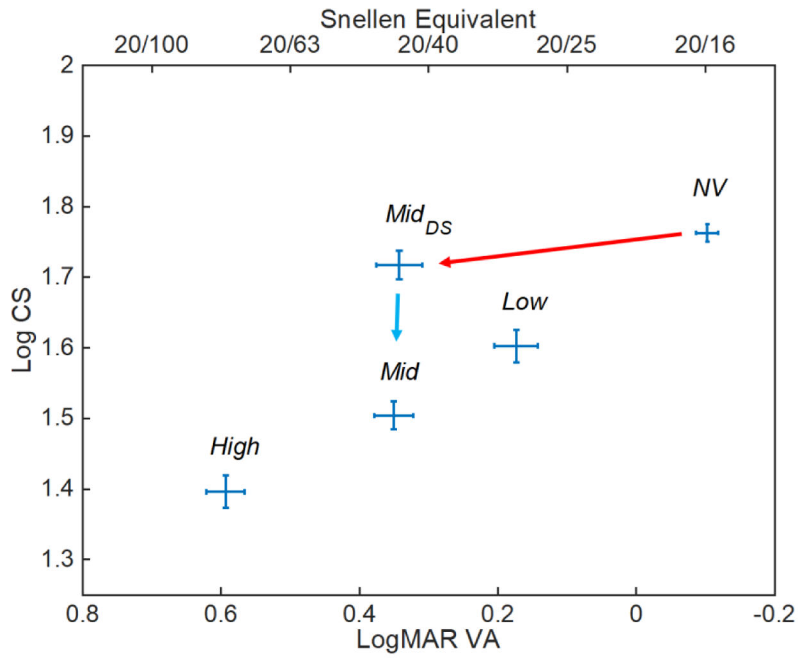

Figure A1.1.

Average contrast sensitive (CS) and visual acuity (VA) for the different conditions (*NV, Low, Mid, High,* Mid_{DS}) in Experiment 1. The red arrow corresponds to the comparison whereby there is only a reduction in VA. The blue arrow corresponds to the comparison whereby there is only a reduction in CS. Error bars are SEM.

When comparing *NV* to Mid_{DS} to determine the effect that a reduction in VA alone has on detection performance (Figure A1.2), there was a marginally significant increase in reaction time [β = 0.03, se = 0.015, t = 2.02, p = 0.044], but no significant increase in deceleration [β = 0.02, se = 0.12, t = 0.17, p = 0.87]. When comparing Mid_{DS} to *Mid,* to determine the effect of adding a CS deficit to the mid-level VA loss, there was a more significant increase in reaction time [β = 0.065, se = 0.019, t = 3.4, p < 0.001] and increase in deceleration [β = 0.39, se = 0.12, t = 3.1, p < 0.005]. Taken together, these results generally replicate the findings from Experiment 2; reductions in CS have a greater impact on detection performance than VA reductions.

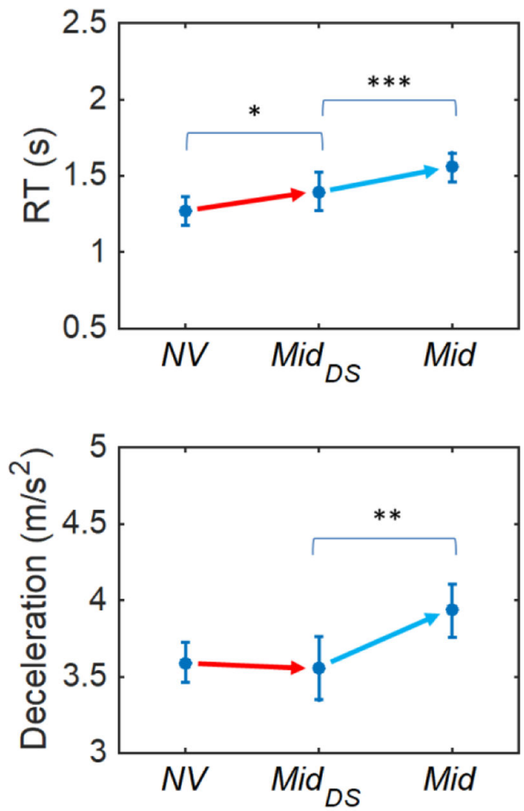

Figure A1.2:
Average reaction time (RT: top row) and deceleration (bottom row) across the different conditions in Experiment 1. The red and blue arrows correspond to the comparison whereby there is only a reduction in VA and CS, respectively. Error bars correspond to SEM. * = $p < .05$, ** = $p < .01$, *** = $p < 0.001$

A1.2 Order effects across Experiments 1 and 2

The effect of the testing order on reaction time and deceleration needed to stop prior to the collision was evaluated using the same LMM structures described in Experiments 1 and 2. The order of the condition (i.e. 1, 2, 3, 4, and 5) was inserted as the fixed effects variable.

Figure A1.3 displays reaction time and deceleration as a function of the order of the test drives for Experiment 1. There was no significant effect of order on reaction time [$\beta = 0.002$, se = 0.003, t = 0.72, p = 0.47] or on deceleration [$\beta = 0.05$, se = 0.03, t = 1.6, p = 0.11].

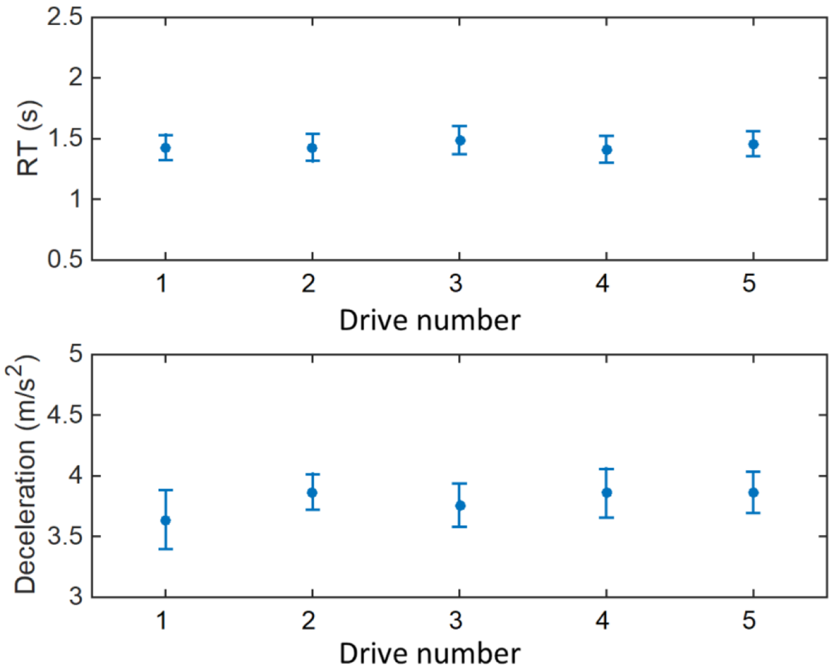

Figure A1.3.

Reaction time (RT: top row) and deceleration (bottom row) are displayed as a function of the order of the drive for Experiment 1.

Figure A1.4 displays reaction time and deceleration as a function of the order of the test drives for Experiment 2. Similar to Experiment 1, there was no significant effect of order on reaction time [$\beta = 0.008$, se = 0.005, t = 1.4, p = 0.16] or on deceleration [$\beta = 0.032$, se = 0.037, t = 0.85, p = 0.39].

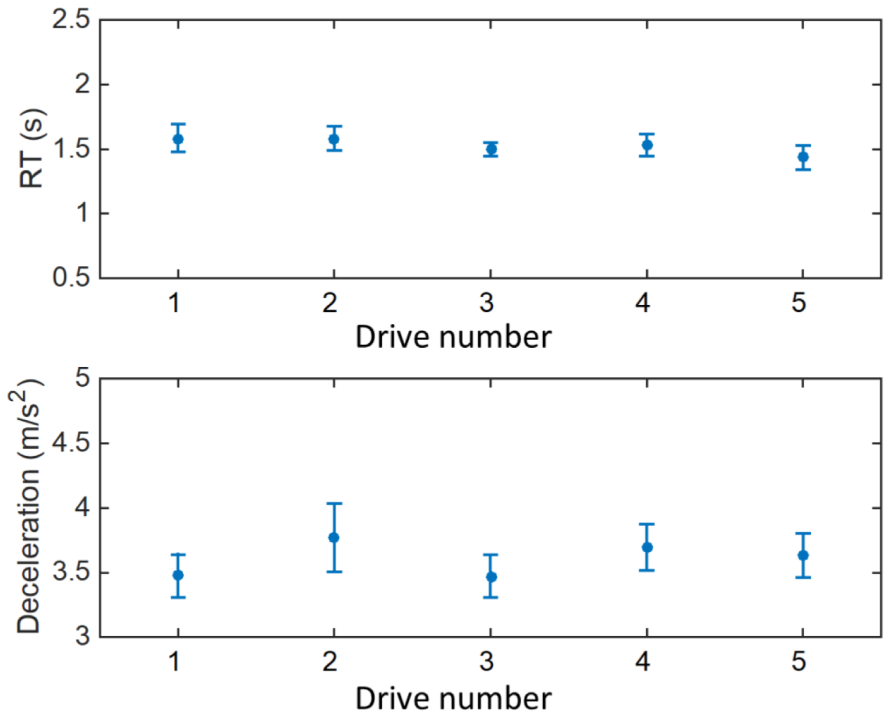

Figure A1.4.
Reaction time (RT: top row) and deceleration (bottom row) are displayed as a function of the order of the drive for Experiment 2.

A1.3 Experiment 2 - Detection performance across different conditions (*NV, Mid, & High*)

In Experiment 2, participants wore the same diffusing filters (*Mid* and *High*) as those used in Experiment 1. In Experiment 1, participants' detection performance decreased as a function of increasing diffusing filter density (section 3.2. in main manuscript). To determine whether those results replicated in Experiment 2, the same analyses conducted in Experiment 1 were conducted in Experiment 2.

As the strength of the diffusing filter increased, the amount of VA [$F(2,14) = 68.7$, $p < 0.001$] and CS [$F(2,14) = 117.7$, $p < 0.001$] impairment significantly increased (see Figure 4 in main manuscript). VA was significantly worse when comparing *Mid* to *NV* [$t(14) = 9.4$, $p < 0.001$] and *High* to *Mid* [$t(14) = 5.8$, $p < 0.001$]. Additionally, CS was significantly worse when comparing *Mid* to *NV* [$t(14) = 33.2$, $p < 0.001$] and *High* to *Mid* [$t(14) = 23.9$, $p < 0.001$].

Reaction time and deceleration are shown in Figure 5 in the main manuscript. There was a significant main effect of condition on reaction time [$\beta = 0.061$, se = 0.013, $t = 4.57$, $p < 0.001$] and deceleration [$\beta = 0.32$, se = 0.10, $t = 3.17$, $p < 0.002$]. Reaction time significantly increased when comparing *NV* to *Mid* [$\beta = 0.083$, se = 0.025, $t = 3.37$, $p < 0.001$], but there was no significant difference between *Mid* to *High* [$\beta = 0.03$, se = 0.02, $t = 1.55$, $p = 0.12$]. The same pattern was found for deceleration: there was a significant increase when comparing *NV* to *Mid* [β = 0.54, se = 0.16, t = 3.3, p < 0.002], but there was no significant difference between *Mid* to *High* [β = 0.06, se = 0.2, t = 0.31, p = 0.75]. There results replicate the general pattern of results found in Experiment 1: participants' detection performance decreases with increasing reductions in CS and VA.

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Highlights

- Simulated vision impairment impaired detection of hazardous pedestrians
- The vision impairment increased reaction time and deceleration to avoid collision
- Contrast sensitivity loss predicted detection performance better than visual acuity
- These results occurred despite visual acuity being within licensure standards

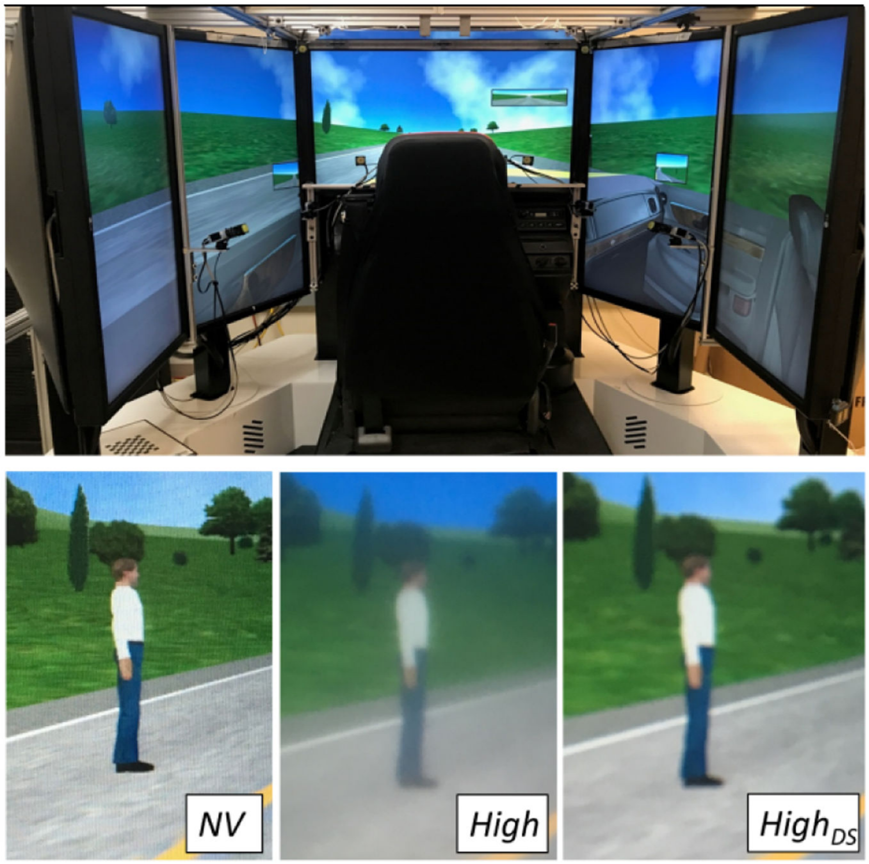

Figure 1:
The driving simulator is displayed in the top row. In the bottom row, the pedestrian is displayed under normal vision (*NV*), under the dense diffusing filter (*High*) used in Experiments 1 and 2 that reduced contrast sensitivity and visual acuity, and under the positive diopter sphere lens ($High_{DS}$) used in Experiment 2 which reduced visual acuity to the same level as *High*, but did not significantly affect contrast sensitivity. These images were taken with a camera with the simulated visual impairment goggles placed in front of the lens, thus representing the subjective experience of wearing the simulated visual impairment.

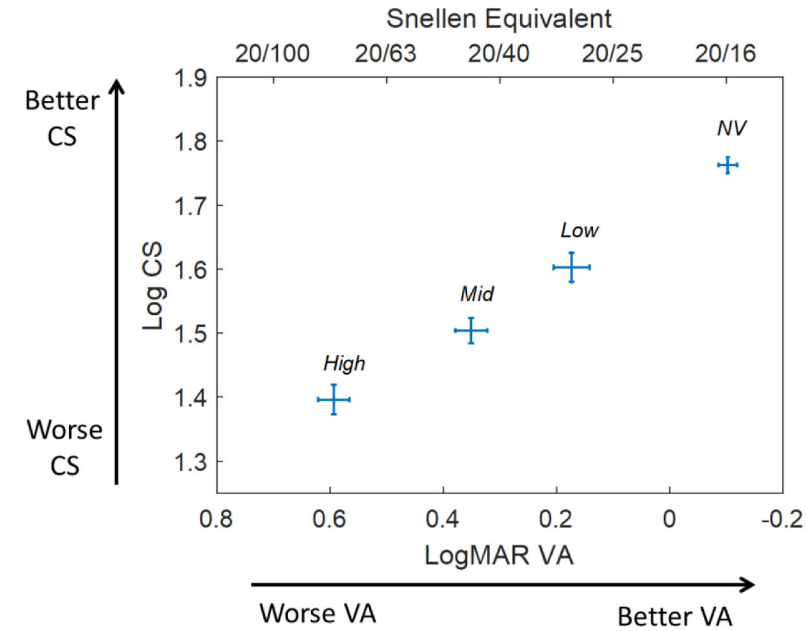

Figure 2.
Average visual acuity (VA) and contrast sensitivty (CS) values across the different conditions in Experiment 1. Error bars are SEM.

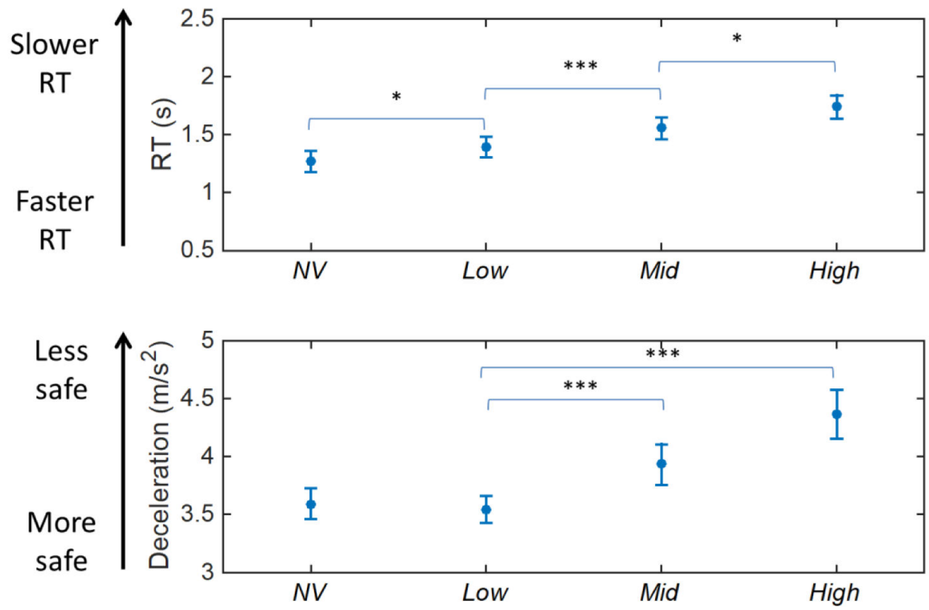

Figure 3:

Average log10 reaction time (RT: top row) and deceleration (bottom row) for the different conditions in Experiment 1. Error bars are SEM. * = $p < .05$, *** = $p < 0.001$

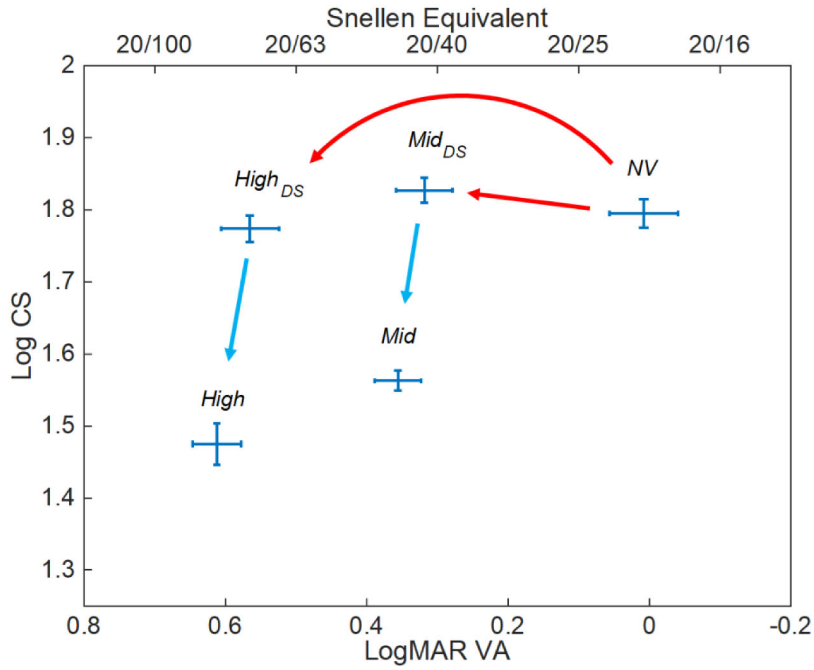

Figure 4:

Average contrast sensitivity (CS) and visual acuity (VA) for the different conditions (*NV, Mid, High,* Mid_{DS}, $High_{DS}$) in Experiment 2. The red arrow corresponds to the comparison whereby there is only a reduction in VA. The blue arrow corresponds to the comparison whereby there is only a reduction in CS. Error bars are SEM.

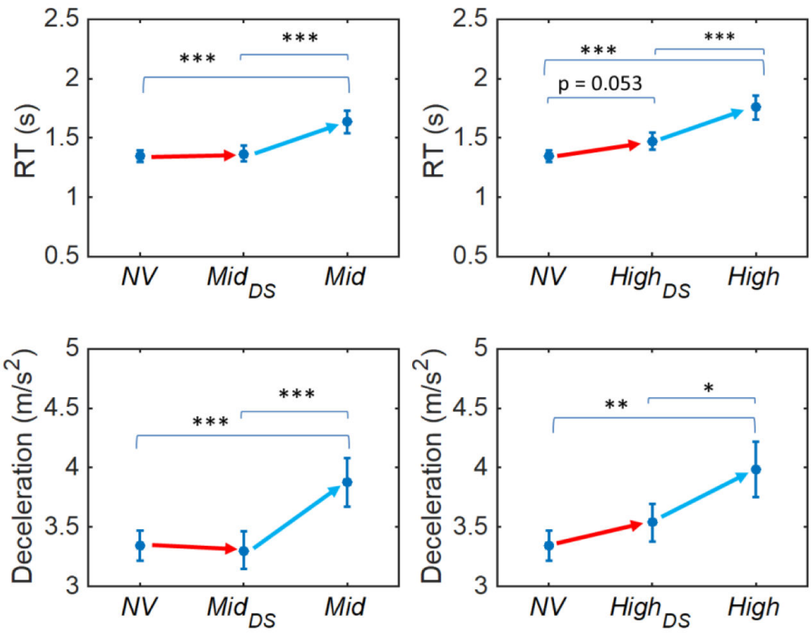

Figure 5:
Average reaction time (RT: top row) and deceleration (bottom row) across the different conditions in Experiment 2. The red arrow corresponds to the comparison whereby there is only a reduction in VA. The blue arrow corresponds to the comparison whereby there is only a reduction in CS. Error bars correspond to SEM. * = $p < .05$, ** = $p < .01$, *** = $p < 0.001$

Table 1:

Average VA, CS, detection rates, reaction times, and deceleration for the different conditions in Experiment 1.

	NV		***Low***		***Mid***		***High***	
Vision measures	**average**	**sem**	**average**	**sem**	**average**	**sem**	**average**	**sem**
VA(logMAR) ⬇	−0.10	0.02	0.17	0.03	0.35	0.03	0.59	0.03
VA (Snellen)	(20/16)		(20/30)		(20/45)		(20/79)	
CS (log) ⬆	1.76	0.01	1.60	0.02	1.50	0.02	1.40	0.02
Driving measures								
Proportion Detected ⬆	0.99	0.01	1.00	0.00	0.99	0.01	0.98	0.01
Car Speed (KPH)	93.7	1.18	93.0	1.11	93.1	1.37	93.9	1.05
Reaction time (s) ⬇	1.27	0.09	1.39	0.09	1.55	0.09	1.73	0.10
Deceleration (m/s^2) ⬇	3.59	0.13	3.54	0.11	3.93	0.17	4.37	0.21

⬆ Higher values mean better performance

⬇ Lower values mean better performance

Table 2:

Average VA, CS, detection rates, reaction times, and deceleration for the different conditions in Experiment 2

	NV		*Mid*$_{DS}$		*High*$_{DS}$		*Mid*		*High*	
Vision measures	**average**	**sem**	**average**	**sem**	**average**	**sem**	**average**	**sem**	**average**	**sem**
VA(logMAR)⬇	−0.03	0.02	0.34	0.03	0.59	0.04	0.34	0.03	0.63	0.03
VA (Snellen)	(20/20)		(20/42)		(20/74)		(20/46)		(20/81)	
CS (log)⬆	1.8	0.02	1.82	0.02	1.78	0.02	1.58	0.02	1.46	0.02
Driving measures										
Proportion Detected⬆	1.00	0.00	0.99	0.01	0.99	0.01	0.99	0.01	0.90	0.00
Car Speed (KPH)	91.3	1.72	90.3	1.94	89.5	1.78	90.9	1.97	90.0	2.01
Reaction time (s) ⬇	1.35	0.05	1.37	0.07	1.47	0.07	1.63	0.09	1.76	0.10
Deceleration (m/s^2) ⬇	3.34	0.13	3.30	0.16	3.53	0.16	3.88	0.20	3.98	0.23

⬆ Higher values mean better performance

⬇ Lower values mean better performance