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Effect of peripheral refractive errors on driving performance

Sonia Ortiz-Peregrina,[1,*] Miriam Casares-López,[1] José J. Castro-Torres,[1] Rosario G. Anera,[1] and Pablo Artal[2]

[1] *Department of Optics, Laboratory of Vision Sciences and Applications, University of Granada, Granada 18071, Spain*
[2] *Laboratorio de Óptica, Universidad de Murcia, Campus de Espinardo, Murcia 30100, Spain*
[*] *soniaortiz@ugr.es*

Abstract: The effect of peripheral refractive errors on driving while performing secondary tasks at 40° of eccentricity was studied in thirty-one young drivers. They drove a driving simulator under 7 different induced peripheral refractive errors (baseline (0D), spherical lenses of +/- 2D, +/- 4D and cylindrical lenses of +2D and +4D). Peripheral visual acuity and contrast sensitivity were also evaluated at 40°. Driving performance was significantly impaired by the addition of myopic defocus (4D) and astigmatism (4D). Worse driving significantly correlated with worse contrast sensitivity for the route in general, but also with worse visual acuity when participants interacted with the secondary task. Induced peripheral refractive errors may negatively impact driving when performing secondary tasks.

1. Introduction

Driving is a highly demanding task that requires the driver to quickly and accurately integrate information from a dynamic environment to control the vehicle and respond safely to the road changes and unexpected events. Vision constitute the input for most of this crucial information, and any degradation could affect driving [1]. Visual information processing is performed by the commonly referred to as the *where* and *what* pathways. The first is responsible for the transmission of location and motion information, through a dorsal route of magnocellular thalamic cells to the occipital and parietal cortex. The second is responsible for the transmission of color and form information, through a ventral route of parvocellular thalamic cells to the occipital and temporal cortex. These two visual pathways process the spatial relationships (*where*) and object information (*what*) [2], key aspects in driving and for which we need to obtain accurate information from the entire visual field. Peripheral vision is fundamental for driving, providing the driver with important information that enables him/her to be aware of road cues, the presence of hazards, or the behavior of other road users [3]. It is important to note that peripheral vision also guides eye movements and visual search, so it therefore guides the visual acquisition process itself, leading the central vision, to the part of the scene with the most essential information [4]. During driving, peripheral vision assists in many aspects such as steering control, lane keeping or hazard avoidance [5–7]. Visual information coming from the peripheral retina is key to alert the driver that something has changed and to know where it has occurred, allowing to plan and execute a response to such events [8,9]. Thus, an accurate integration of information results in safe behaviors and in the avoidance of potential accidents. In fact, a recent study has shown that drivers respond to hazards before fixating them, guiding the response by information acquired in peripheral vision [10].

It has been demonstrated that alterations in the visual field due to ocular disease significantly impair driving performance and increase accident risk. Losses in peripheral visual field sensitivity seem to be associated with higher rates of accidents [11]. Wood and Troutbeck [12] demonstrated that simulated reductions in the binocular visual field to ± 20° or less may affect driving

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performance in aspects such as road sign identification, obstacle avoidance and maneuvering. Lower anticipation skills have been found in drivers with glaucoma [13], as well as more incidence of critical errors, even for those with early and mild stages of the disease [14].

One of the most widely used tests to evaluate the region of the visual field where a driver could process information is the so-called Useful Field of View (UFOV) [15]. Despite their validated predictive power for accident involvement in older drivers [16], this conception of the useful visual field (occupying around 15°- 20°), neglects the usefulness of much of the extent of peripheral vision [17]. The entire human visual field assists in the integration of information for situational awareness of the driving environment [18], lane keeping, and hazard detection [5–7]. Moreover, current trends in in-vehicle environments, with cars equipped with sophisticated navigation and infotainment systems, highlights the importance of peripheral vision for carrying out secondary tasks while driving. Also, the emergence of autonomous driving may suppose the driver shifts his/her gaze away from the road for more prolonged periods of time to perform secondary tasks. Therefore, it is essential to take into account the capabilities and limitations of vision over the entire field of view.

Peripheral vision is not only affected by ocular pathologies, but also by peripheral refractive error that may reduce the optical quality of the eye in the periphery of the retina. In normal eyes, the incidence of oblique off-axis astigmatism has long been demonstrated [19]. Although the average oblique astigmatism appears to be the same regardless of foveal refraction, the radial and tangential refractions vary in their relationship to the central refraction among myopic, emmetropic and hyperopic observers [20]. Several studies have also found that myopic eyes have a more relative hyperopic peripheral refractions than emmetropic and hyperopic eyes [20–22]. On the other hand, there are several conditions/interventions that may affect peripheral optical quality in active drivers. An example is cataract surgery, a procedure that 28 million people undergo each year worldwide [23]. It has been shown that pseudophakic eyes implanted with standard monofocal IOLs (intraocular lenses) suffer impairments in peripheral optical quality compared to normal eyes [24], with significantly greater defocus and astigmatism [25], and worse contrast sensitivity in the peripheral retina [26]. This is an important visual function for driving performance [27,28]. A significant proportion of the patients who undergo cataract surgery have active lifestyles, driving daily. Venkatamaran et al. [29] studied phakic participants simulating typical peripheral optical errors induced by monofocal IOLs. Subjects were evaluated for visual acuity, contrast sensitivity and a hazard detection task that tried to imitate a driving situation. The authors demonstrated that peripheral optical errors reduced visual acuity and contrast sensitivity, but also negatively affected hazard detection with higher reaction times [29]. Another issue is related to myopia, which has become a pandemic [30]. Some current optical treatments on myopia control are based on inducing peripheral myopic defocus: orthokeratology (OK), soft contact lenses or ophthalmic lenses [31–33]. These interventions are usually performed in younger subjects that could be inexperienced drivers.

These changes on peripheral optics could affect vision and therefore the ability for driving, even when drivers could be not aware of. Drivers with ocular pathologies affecting peripheral vision such as glaucoma, commonly self-regulate their driving, avoiding situations such as driving at night or in remote areas [34]. However, drivers with conditions such as those discussed above may be not aware, supposing a danger to older drivers, as well as to young drivers with limited experience. The risk may be even higher when the subject combines driving the car with a secondary task, forcing them to control the road with their peripheral vision.

In this context, the objective of this study was to investigate the effect of peripheral refractive errors on driving while performing secondary tasks. Also, an additional aim was to establish which test for evaluating the quality of peripheral vision could be more predictive of driving performance.

2. Methods

2.1. Participants

The study included 31 young volunteers (mean age ± SD; 24.19 ± 4.92 years; range 19-39 years), from which 16 were males (51.6%). Inclusion criteria covered the following aspects: being regular driver (i.e. driving at least once a week) and have a valid driving license, binocular visual acuity of at least 20/25, no binocular or accommodative disorders, no ocular disease or previous ocular surgeries. All participants had low central/foveal refractive errors (i.e. spherical equivalent between +/- 1.50 D) to secure a group with relatively similar peripheral refractions [21]. According to Jaeken and Artal [35], spherical equivalent at 40° (temporal and nasal retina) in subjects with these central refractive error would range from approximately +0.25D to -2.50D.

This work followed the tenets of the Declaration of Helsinki and an informed consent was obtained from each participant. This study was prospectively approved by the University of Granada's Ethics Research Committee (921/CCEIH/2019).

2.2. Driving simulator

To assess participant's driving performance, a fixed-base driving simulator was employed (SIMAX DRIVING SIMULATOR v4.0.8 BETA, SimaxVirt, Pamplona, Spain). The simulator provided 180° field of view, and a full description of the equipment can be found in Ortiz et al. [36]. Participants completed a 9.2 km route that comprised two different sections: dual carriageway and mountain road. The dual carriageway section was 4.5-km-long, had two lanes of traffic in each direction, 120 kph speed limit, and a mainly straight layout, with only gentle curves. The mountain road section was 4.7-km-long, had one lane of traffic in each direction (oncoming traffic), 40 and 90 kph speed limits and a winding layout. All participants drove a route with identical traffic flow and peripheral events. They received a training session that lasted about 15 minutes, driving routes similar to those employed in the experimental sessions. All of them assert they felt comfortable with the operation of the simulator at the end of the training session.

The following driving variables were considered for analysis to assess driving performance: mean speed (kph), mean time to complete the section (s), distance driven invading the opposite lane (m), distance driven onto the shoulder (m), total distance driven outside the lane (m), standard deviation (SD) of the angular velocity of the steering wheel (rad/s), standard deviation of the lateral lane position (SDLP, m). In order to obtain more information about lane keeping in the dual carriageway, participants were instructed to drive in the right lane. Finally, as an overall measure of driving performance, we obtained the Overall Driving Performance Score (ODPS). This score is computed by calculating the z-scores of each independent variable and averaging them. Z-scores are a measurement of how many standard deviations an individual value is away from the group mean. In other words, it is a statistic used to compare the result of one subject with the result of the whole group. Thus, Z-score is computed as follows: $z = (x - \mu) / \sigma$ (where x is the variable value for a certain subject; μ is the mean for this variable in the whole group; and σ is the standard deviation of the variable in the whole group). Z-scores were reversed in order to achieve that positive values represent better performance than the mean [28,37–40]. To obtain the ODPS, we did not consider the distance driven onto the shoulder and the distance driven invading the opposite lane given that these variables are included in the total distance driven outside the lane. Mean speed and total time were not considered either, since a higher or lower speed does not imply better or worse performance.

2.3. Procedure

After the driving simulator training protocol, participants completed a total of 7 experimental conditions divided in two experimental sessions of about 1 hour. On each experimental condition, they had to drive the route with a specific peripheral refractive error (a more detailed description on this aspect is included below). At some points during driving, they performed secondary tasks in a 10'' touch screen that simulates an infotainment or navigation system positioned at 40° to the right of the driver relative to a straight line from the driver's eyes towards the road in front (Fig. 1). We selected this eccentricity due to several reasons. Important changes have been found in peripheral refractive error in patients after cataract surgery [25] or under treatments as orthokeratology [41] at similar angles. Furthermore, the selected eccentricity was based on previous studies [42,43] and went along with the safety guidelines for in-vehicle information systems of agencies such as the Japan Automobile Manufacturers Association (JAMA) [44]; or the European Statement of Principles (ESOP) [45]. Their main recommendations with regard to the display position are to limit the downward moving angle to 30° and not to obstruct the visibility of the forward field. The drivers sat at approximately the same height as the monitor, so they did not have to move their gaze vertically and the position selected did not obstruct the visibility of the forward field in the simulator. The secondary task screen was placed over the right screen of the simulator, covering some of the visual information provided by it, but retaining the rear-view mirror information. Placing the display on the ride side allowed us not to block the view of the left rearview mirror, which provided more relevant information about the driving environment (e.g. on the position relative to the lane dividing line or oncoming traffic).

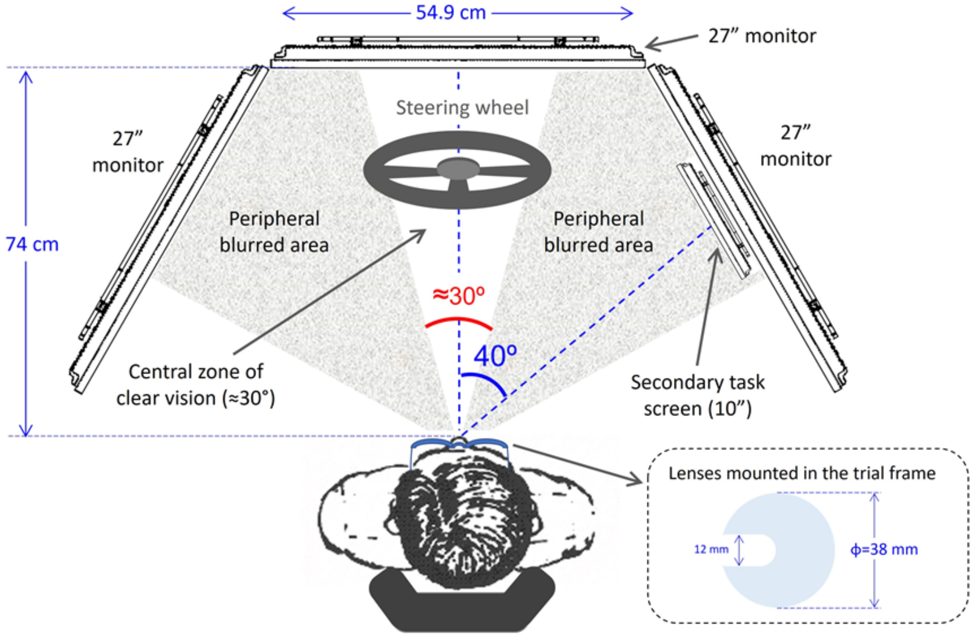

Fig. 1. Schematic view of the experimental setup

For the secondary task display to subtend this visual angle, drivers had to be 74 cm away from the simulator's front display. In some cases, it was not possible to drive at this distance comfortably, so participants were allowed to adjust the seating position as little as possible. Sixteen drivers had to adjust their seat distance (range 63-79 cm), driving with the secondary task's monitor at a range of eccentricities from 38.7° to 43.5°). The order of the experimental conditions was randomized in order to avoid learning effects.

2.4. Peripheral refractive errors and visual assessment

Participants drove without inducing additional peripheral refractive errors (baseline session) and under different induced values of peripheral defocus and astigmatism. For this purpose, we employed ophthalmic lenses mounted in a trial frame (38 mm of diameter). The lenses induced peripheral refractive errors, without restricting the horizontal extension of the binocular visual field required by the licensing standards in Europe (120°) [46,47]. The lenses, with no rims on the edges, had a corridor in the central area towards the nasal area to enable a clear vision over an approximately ±15° extension of the central field of view (Fig. 1). Clear central vision with the lenses was experimentally verified by measuring central visual acuity in different subjects with and without the lenses, finding the same values in both conditions.

We selected six different values of induced peripheral refractive errors generated with spherical lenses of +/- 2.00D, +/- 4.00D (myopic and hyperopic defocus) and cylindrical lenses of +2.00D and +4.00D oriented at 180° (with the rule astigmatism). The baseline condition was performed wearing the same trial frame used in the experimental conditions without lenses mounted.

Before starting experimental sessions under each peripheral induced refractive error, participants were always asked if they were comfortable, and if they could see the central field of the simulator without any distortion. They were also asked to indicate the approximate location (on the simulator screens) where they started to see blurred at the periphery.

On each experimental condition, peripheral visual acuity and peripheral contrast sensitivity were also assessed. For this purpose, we employed the tests implemented in the Bueno-Matilla vision unit (UBM) (Optonet Ltd, Warrington, Cheshire, UK) for near vision, calibrated to the distance at the secondary task screen (58 cm) where stimuli were displayed on a 10'' monitor at an eccentricity of 40°. The UBM unit is a CE certified medical device for Class I visual examination, registered with the British Medicines and Healthcare products Regulatory Agency under reference number 5943 (https://optonet.es/).

Peripheral visual acuity was evaluated with the test of symmetrical letters (logMAR notation) by isolating letters. Participants had to respond correctly to at least 2 of 3 presentations for each level. The size of the letters varied in geometrical progression with a factor of 1.26, considered as more physiological than decimal, guaranteeing regular and equal steps.

Peripheral contrast sensitivity was evaluated with isolated letters of an equivalent visual acuity of 0.025 (decimal notation), a size that participants were able to detect with relative comfort at maximum contrast (100%). Contrast varied from 100% (0.0 log units) to 0.5% (2.30 log units) in 0.15 log units' steps.

2.5. Secondary task

Participants performed peripheral secondary tasks while driving under different induced additional peripheral refractive errors (Fig. 2). The first task consisted of searching for and identifying a road sign in a document in which a different sign appeared at the center of each page. At specific points of the route, they were asked to search a specific traffic road sign and they had to browse in the document with the touch screen until they found and left it on the screen. This task was repeated 3 times in the dual-carriageway and 3 times in the mountain road. The size of road signs was adjusted in such a way that the detail subtended an angle of one arcminute, then equivalent to a stimulus that should be detected with a visual acuity of 6/6 (Snellen notation). The second task consisted of entering an address into Google Maps and was performed only once at a specific point on the mountain road. While performing the secondary tasks (both the Google Maps task and the road sign search task), participants were allowed to direct their gaze wherever they wanted, distributing their visual attention as they considered most efficient, as would be done in a real situation. Also, if they considered the situation too dangerous to engage in a secondary task, they could leave them and reengage at a later time.

2.6. Statistical analysis

The statistical analysis was performed with the software SPSS v.26 (SPSS Inc., Chicago, IL). The data distribution was tested with the Kolmogorov Smirnov test. To study the effect of the

Fig. 2. Illustration of the secondary peripheral tasks employed in the study.

condition (peripheral refractive error) on driving performance variables and visual parameters, when normality of data distribution could be assumed, an ANOVA test was employed, with peripheral defocus as a factor. Post hoc pairwise comparisons were also studied, applying Bonferroni's correction. When normality could not be assumed, a Friedman test was applied, also using Bonferroni's correction for pairwise comparisons. To explore the relationship between visual status and driving performance for all conditions, a bivariate correlation analysis (Spearman's correlation) including visual parameters and the overall driving performance score (ODPS) was performed. Data has been analyzed for the whole route and also for the segment when participants were interacting with the Google Maps secondary task, as this is considered more visually demanding. Statistical significance was set at 0.05 level.

3. Results

3.1. *Visual performance*

Peripheral visual acuity and contrast sensitivity are presented in Table 1. As indicated by the pairwise comparisons results (all with respect to baseline condition), peripheral visual acuity was significantly deteriorated for all conditions, except for 2D of hyperopic defocus. Similarly, peripheral contrast sensitivity also deteriorated for all induced defocuses, except for 2D of myopic defocus, which also impaired contrast sensitivity, but not significantly. The greatest impairment was found for the defocus of +4D and -4D, and for +4D of astigmatism. No significant differences in peripheral visual acuity and contrast sensitivity were observed between +2D and -2D and between +4D and -4D.

Table 1. Mean values ± SD of peripheral visual acuity (VA) and peripheral contrast sensitivity (CS) for the different spherical (SPH) and astigmatic (AST) defocuses[a]

	VA (logMAR)	*Log CS*
Statistic **p-value**	59.853 p<0.001	62.364 p<0.001
Baseline	1.10 ± 0.15	1.32 ± 0.18
SPH +2D	1.19 ± 0.12 p=0.021	1.22 ± 0.17
SPH-2D	1.16 ± 0.12	1.19 ± 0.15 p=0.036
SPH +4D	1.24 ± 0.11 p<0.001	1.07 ± 0.21 p<0.001
SPH -4D	1.27 ± 0.11 p<0.001	1.07 ± 0.19 p<0.001
AST +2D	1.18 ± 0.14 p=0.019	1.17 ± 0.18 p=0.012
AST +4D	1.25 ± 0.15 p<0.001	1.03 ± 0.20 p<0.001

[a] P-values and the statistic are also included, as well as the significant p-values resulting from comparing each defocus with the baseline condition.

3.2. Driving performance

General route (all secondary tasks)

Mean driving performance results from the general route (which included all tasks performed in the whole route) are represented in Tables 2 and 3. In the dual carriageway, a significant decrease of the mean speed along with an increase of the mean time taken to complete the course was obtained for the different defocuses. As can be observed in Tables 2 and 3, pairwise comparisons (all with respect to the baseline condition) showed that these changes were significant for 2D of myopic defocus, 4D of hyperopic defocus, and +2D and +4D of astigmatism. The distance driven invading the opposite lane also increased significantly, as well as the total distance driven outside the lane for +2D and +4D of astigmatism, respectively.

In the mountain road, a significant decrease of the mean speed and an increase of the mean time was also observed among the different defocuses, with these differences being significant for +4D of astigmatism. The SD of the angular velocity of the steering wheel increased significantly, particularly for +4D of spherical defocus. Likewise, the SDLP increased, especially for 4D of myopic defocus and +4D of astigmatism.

The overall driving performance score (ODPS) decreased for the different conditions compared to the baseline condition (Fig. 3). Pairwise comparisons showed that driving performance was significantly impaired by 4D of myopic defocus and +4D of astigmatism (Tables 2 and 3). This ODPS was correlated with the contrast sensitivity (ρ=0.201; p=0.003), but a significant association was not observed for the visual acuity.

Table 2. Mean values ± SD of the driving variables for the different induced defocuses.[a]

		Statistic (p-value)	**Baseline**	**SPH +2D**	**SPH -2D**	**SPH +4D**
Dual carriageway	***Mean speed (kph)***	17.119 p=0.009	105.83 ± 6.20	101.15 ± 7.44 p=0.006	103.01 ± 7.35	102.33 ± 7.86
	Mean time (s)	16.590 p=0.011	144.18 ± 8.93	151.09 ± 11.10 p=0.012	148.46 ± 11.76 p=0.066	149.58 ± 12.96 p=0.060
	Distance driven invading the opposite lane (m)	12.641 p=0.049	121.13 ± 116.17	137.72 ± 109.09	142.77 ± 176.65	177.06 ± 176.56
	Distance driven onto the shoulder (m)	11.584 p=0.072	53.69 ± 74.40	49.49 ± 69.11	40.97 ± 50.40	81.69 ± 114.11
	Total distance driven outside the lane (m)	16.430 p=0.012	174.81 ± 157.51	187.20 ± 131.14	183.74 ± 194.11	258.76 ± 232.95
	SD angular velocity of the steering wheel (rad/s)	10.242 p=0.115	0.21 ± 0.07	0.20 ± 0.06	0.20 ± 0.07	0.23 ± 0.11
	SDLP (m)	10.472 p=0.106	0.51 ± 0.12	0.50 ± 0.10	0.50 ± 0.11	0.55 ± 0.16
Mountain road	***Mean speed (kph)***	15.462 p=0.017	56.59 ± 2.92	56.38 ± 2.53	56.29 ± 2.83	55.17 ± 3.64
	Mean time (s)	13.808 p=0.032	296.94 ± 33.84	297.56 ± 13.80	301.80 ± 26.09	305.39 ± 22.21
	Distance driven invading the opposite lane (m)	7.662 p=0.264	264.23 ± 192.30	276.32 ± 150.08	303.07 ± 189.09	345.63 ± 249.37
	Distance driven onto the shoulder (m)	8.998 p=0.174	74.33 ± 92.87	102.75 ± 116.45	97.88 ± 110.58	121.21 ± 119.60
	Total distance driven on the shoulder (m)	11.221 p=0.082	338.57 ± 208.21	379.09 ± 189.65	400.95 ± 205.80	466.84 ± 264.24
	SD angular velocity of the steering wheel (rad/s)	13.258 p=0.039	0.53 ± 0.18	0.55 ± 0.12	0.54 ± 0.15	0.56 ± 0.11 p=0.024
	SDLP (m)	31.321 p<0.001	0.60 ± 0.09	0.63 ± 0.10 p = 0.072	0.62 ± 0.11	0.71 ± 0.19 p<0.001
	ODPS	23.082 p<0.001	0.19 ± 0.59	0.12 ± 0.51	0.14 ± 0.55	-0.25 ± 0.83 p<0.001

[a] P-values and the statistic are also included, as well as significant p-values resulting from comparing each defocus with the baseline condition.

Table 3. Mean values ± SD of the driving variables for the different induced defocuses.[a]

		Statistic (p-value)	Baseline	SPH -4D	AST +2D	AST +4D
Dual carriageway	***Mean Speed (kph)***	17.119 p=0.009	105.83 ± 6.20	101.61 ± 8.34 p=0.018	102.40 ± 6.50 p=0.024	100.98 ± 7.61 p<0.001
	Mean time (s)	16.590 p=0.011	144.18 ± 8.93	150.64 ± 13.05 p=0.018	149.08 ± 10.00 p=0.024	151.46 ± 12.05 p<0.001
	Distance driven invading the opposite lane (m)	12.641 p=0.049	121.13 ± 116.17	166.07 ± 166.01	185.37 ± 144.59 p=0.024	168.92 ± 123.68 p=0.096
	Distance driven onto the shoulder (m)	11.584 p=0.072	53.69 ± 74.40	84.43 ± 91.55	73.23 ± 88.13	82.50 ± 123.50
	Total distance driven outside the lane (m)	16.430 p=0.012	174.81 ± 157.51	250.51 ± 191.80	258.61 ± 171.15	251.42 ± 200.16 p=0.012
	SD angular velocity of the steering wheel (rad/s)	10.242 p=0.115	0.21 ± 0.07	0.22 ± 0.08	0.20 ± 0.04	0.22 ± 0.07
	SDLP (m)	10.472 p=0.106	0.51 ± 0.12	0.54 ± 0.12	0.54 ± 0.11	0.54 ± 0.13
Mountain road	***Mean speed (kph)***	15.462 p=0.017	56.59 ± 2.92	55.50 ± 3.37	56.74 ± 2.84	54.71 ± 3.21 p=0.006
	Mean time (s)	13.808 p=0.032	296.94 ± 33.84	303.91 ± 21.65	296.92 ± 15.18	309.06 ± 19.30 p=0.006
	Distance driven invading the opposite lane (m)	7.662 p=0.264	264.23 ± 192.30	281.73 ± 157.32	312.91 ± 187.41	306.08 ± 173.67
	Distance driven onto the shoulder (m)	8.998 p=0.174	74.33 ± 92.87	75.13 ± 89.05	87.75 ± 104.49	96.32 ± 119.13
	Total distance driven on the shoulder (m)	11.221 p=0.082	338.57 ± 208.21	356.89 ± 174.12	400.66 ± 203.97	402.39 ± 204.00
	SD angular velocity of the steering wheel (rad/s)	13.258 p=0.039	0.53 ± 0.18	0.57 ± 0.18	0.53 ± 0.12	0.59 ± 0.20
	SDLP (m)	31.321 p<0.001	0.60 ± 0.09	0.61 ± 0.09	0.63 ± 0.11	0.71 ± 0.33 p<0.001
	ODPS	23.082 p<0.001	0.19 ± 0.59	-0.02 ± 0.59	0.00 ± 0.58	-0.19 ± 0.73 p=0.012

[a] P-values and the statistic are also included, as well as significant p-values resulting from comparing each defocus with the baseline condition.

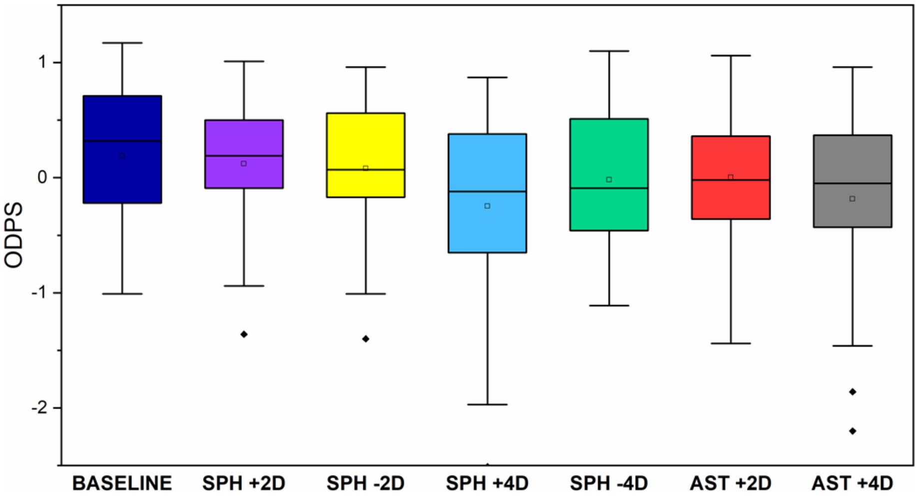

Fig. 3. Overall driving performance score (ODPS) of the general route for the different defocuses.

Google Maps task

The results of the driving variables for the section where the Google Maps task was performed are shown in Tables 4 and 5. These values indicated that the mean speed decreased for the different defocuses with respect to baseline, particularly for 4D of myopic defocus, 4D of hyperopic

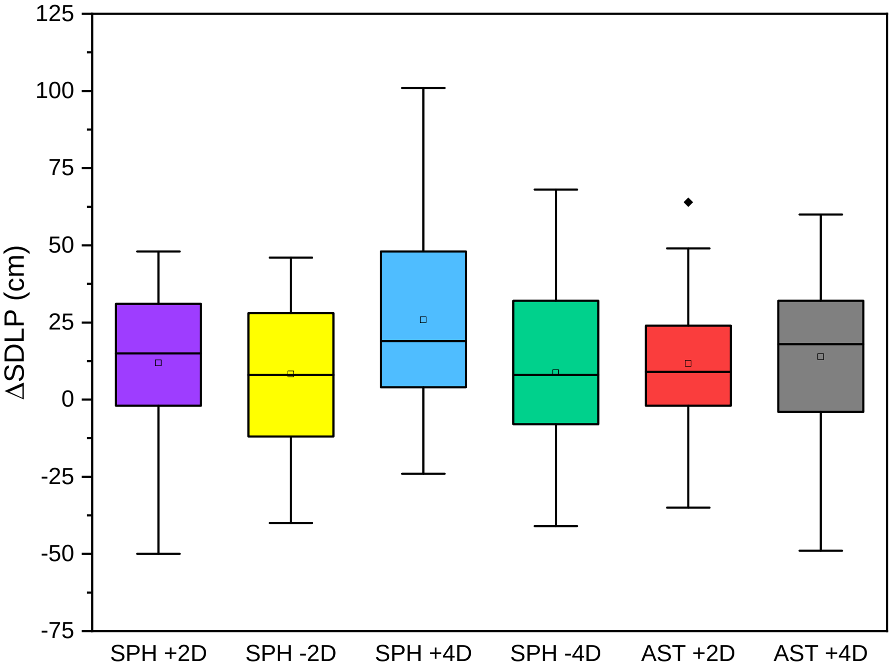

Fig. 4. Increase (Δ) of the standard deviation of the lateral position (SDLP) for the different defocuses with respect to baseline condition.

defocus, and +2D and +4D of astigmatic defocus according to pairwise comparisons (all with respect to baseline). Therefore, the time required to complete the course increased significantly for 4D of myopic defocus, and +2D and +4D of astigmatism. The distance driven invading the opposite lane and the total distance driven outside the lane, showed significant differences for 4D of myopic defocus and +4D of astigmatism. Likewise, the SD of the angular velocity of the steering wheel and the SDLP were also higher for the different defocuses, especially for 4D of myopic defocus. This increase of the SDLP is represented in Fig. 4.

Table 4. Mean values ± SD of the driving variables in the section corresponding to the Google Maps task.[a]

		Statistic (p-value)	**Baseline**	**SPH +2D**	**SPH -2D**	**SPH +4D**
Google Maps task – driving performance	***Mean Speed (kph)***	23.820 p=0.001	60.01 ± 9.14	54.44 ± 8.02	56.20 ± 8.76	51.48 ± 10.03 p=0.001
	Mean time (s)	21.460 p=0.002	28.39 ± 22.17	33.16 ± 15.73	30.01 ± 13.55	41.44 ± 24.72 p=0.003
	Distance driven invading the opposite lane (m)	13.773 p=0.032	31.19 ± 43.44	48.08 ± 51.58	48.50 ± 60.50	65.12 ± 62.23 p=0.016
	Distance driven onto the shoulder (m)	11.231 p=0.081	25.70 ± 45.95	31.40 ± 32.67	26.43 ± 34.04	50.75 ± 59.68
	Total distance driven outside the lane (m)	16.940 p=0.010	56.89 ± 62.31	79.48 ± 62.27	74.92 ± 66.51	115.86 ± 100.81 p=0.006
	SD angular velocity of the steering wheel (rad/s)	12.803 p=0.046	0.47 ± 0.26	0.52 ± 0.20	0.48 ± 0.29	0.57 ± 0.17 p=0.006
	SDLP (m)	21.578 p=0.001	0.31 ± 0.23	0.73 ± 0.22	0.69 ± 0.18	0.87 ± 0.26 p<0.001
	ODPS	15.952 p=0.014	0.35 ± 0.77	0.02 ± 0.75	0.14 ± 0.74	-0.40 ± 0.92 p=0.005

[a] P-values and the statistic are also included, as well as significant p-values resulting from comparing each defocus with the baseline condition.

The ODPS (Tables 4 and 5) showed that, similarly to the ODPS obtained for the general task, the driving performance was poorer for the different defocuses compared to the baseline, but mainly for 4D of myopic defocus and +4D of astigmatism, the two most impairing conditions (Fig. 5). The ODPS of the Google Map task was significantly associated with both the visual acuity (ρ=-0.192; p=0.004) and the contrast sensitivity (ρ=0.262; p<0.001).

Table 5. Mean values ± SD of the driving variables in the section corresponding to the Google Maps task.[a]

		Statistic (p-value)	Baseline	SPH -4D	AST +2D	AST +4D
Google Maps task – driving performance	*Mean Speed (kph)*	23.820 p=0.001	60.01 ± 9.14	52.65 ± 10.01 p=0.04	52.97 ± 7.68 p=0.010	50.03 ± 7.75 p<0.001
	Mean time (s)	21.460 p=0.002	28.39 ± 22.17	34.41 ± 17.93	30.70 ± 11.42 p=0.038	40.44 ± 20.05 p=0.002
	Distance driven invading the opposite lane (m)	13.773 p=0.032	31.19 ± 43.44	47.59 ± 42.47	60.57 ± 61.34	67.51 ± 61.34 p=0.011
	Distance driven onto the shoulder (m)	11.231 p=0.081	25.70 ± 45.95	25.78 ± 35.71	28.69 ± 46.62	33.87 ± 44.40
	Total distance driven outside the lane (m)	16.940 p=0.010	56.89 ± 62.31	73.37 ± 66.06	89.26 ± 75.61	101.38 ± 82.93 p=0.024
	SD angular velocity of the steering wheel (rad/s)	12.803 p=0.046	0.47 ± 0.26	0.61 ± 0.38	0.49 ± 0.20	0.52 ± 0.16
	SDLP (m)	21.578 p=0.001	0.31 ± 0.23	0.70 ± 0.28	0.73 ± 0.21	0.75 ± 0.23
	ODPS	15.952 p=0.014	0.35 ± 0.77	-0.03 ± 1.03	0.02 ± 0.77	-0.11 ± 0.77 p=0.009

[a] P-values and the statistic are also included, as well as significant p-values resulting from comparing each defocus with the baseline condition.

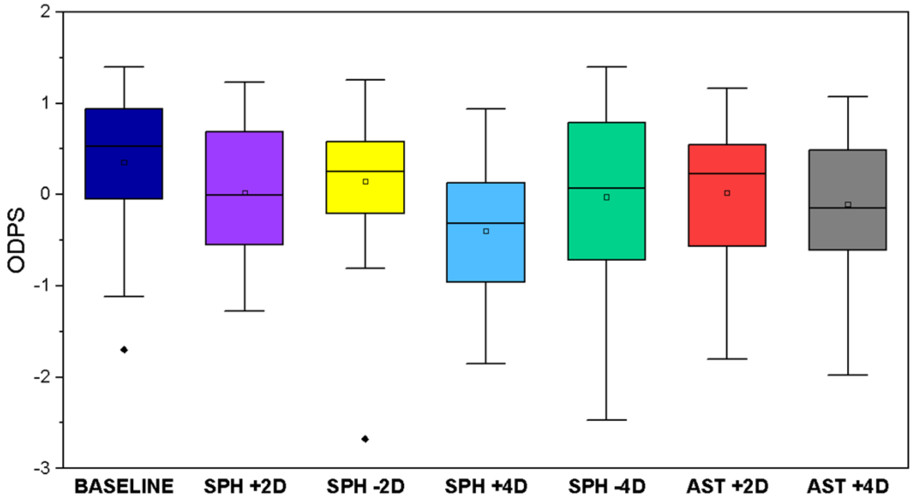

Fig. 5. Overall driving performance score (ODPS) of the Google Maps task for the different defocuses.

4. Discussion

Peripheral refractive errors negatively impact driving when performing secondary visual-manual tasks similar to those a driver could conduct when at the wheel. General driving performance has been mainly impaired by the addition of 4D of myopic defocus and 4D of astigmatism. The impairment in general driving performance (ODPS) was significantly correlated with poorer peripheral contrast sensitivity for the route in general, but also with worse visual acuity for the secondary task.

Moderate but significant impairments have been found for peripheral visual acuity and contrast sensitivity in the different defocus conditions. On this regard, it has been shown that detection and resolution acuity is affected differently by peripheral optical defocus. This is due to the sampling limited nature of peripheral resolution. Thus, detection performance seems markedly higher in the periphery than resolution performance which is quite robust to refractive blur [48], explaining the moderate changes found in our study. Several investigations have evaluated both aspects after correcting intrinsic peripheral refractive errors. Anderson et al. [49] found that at 30°, detection acuity was higher than resolution acuity. Between -2D and +2.5 D, resolution performance remained constant while detection performance constantly decreased with defocus. Artal et al. [50] studied the detection and motion discrimination of sinusoidal gratings at 20° and 40° horizontally. The authors found that the highest detected frequency depended primarily on peripheral refraction, as opposed to direction discrimination. Likewise, Thibos et al. [51] studied grating detection and resolution and showed that increases of about 10% in contrast resulted in improvements of detection performance, but resolution did not improve. By using vanishing optotypes (i.e. pseudo high-pass letters whose average luminance is assimilated to that of the background, until they disappear), Shah et al. [52] showed similar results. The authors indicated that at 0 D of defocus in the periphery, recognition thresholds were significantly higher than detection thresholds, but both increased steadily thereafter, converging as defocus increased up to 7 D.

High order aberrations also play an important role in the deterioration of the peripheral optical quality. Coma becomes especially relevant in peripheral vision, since it increases with eccentricity, reaching values of 0.4 µm at 40° (temporal) [53]. Coma, along with peripheral horizontal astigmatism, are the main responsible for the deterioration of the peripheral image quality, leading to an asymmetry in depth of field, particularly in myopes [53,54]. Considering these findings, it seems reasonable that peripheral visual acuity would be more impaired when simulating high peripheral horizontal astigmatism, as obtained in this study. Also, it seems there are no differences in sensitivity when comparing positive and negative defocuses in emmetropes (the majority in our sample) [54]. In this sense, we observed no significant differences in visual acuity and contrast sensitivity between +2D and -2D, nor between +4D and -4D.

With regard to driving performance, specific aspects such as the SD of the angular velocity of the steering wheel in the mountain road and the SDLP have shown that the greater myopic defocus, as well as astigmatism can generate poorer lane maintenance. When performing the Google Maps task, for which more sensitive visual resolution is required, the impact on lane keeping variables are even more remarkable with respect to the baseline session than for the route in general (all tasks). Peripheral vision is important for driving performance since while drivers are directing their gaze off-road, it is used to operate the vehicle in aspects such as lane keeping, the detection of oncoming vehicles or forward hazards. On this regard, it has been studied the influence of glance direction to a secondary task on lane keeping, finding that performance can decrease with increasing eccentricities and that the driver can learn to keep the vehicle within the lane by employing peripheral vision [55]. Moreover, when the driver's gaze is directed to the road, peripheral vision of the road's edges, as well as the optic flow are employed to guide steering and to estimate the vehicle's position within the lane [5,56]. With regard to the longitudinal control of the vehicle, this study found significant reductions in speed (as well as increased time to complete the route) with respect to the baseline condition (without imposing additional peripheral refractive error). These reductions were found for the defocuses generated by the +2D and -4D spheres, and for both cylinders (+2D and +4D). When performing the Google Maps task, speeds were significantly decreased for the +/- 4D sphere and for both cylinders. These results may reflect an awareness of visual impairment among drivers, who try to self-regulate in order to compensate for this impairment and to maintain the risk within acceptable limits. Other studies have found that visual status may influence how drivers self-regulate their driving speed [57,58]. Also, vision has demonstrated to play an important role on how older drivers self-regulate their driving [59,60].

Moreover, worse overall driving performance scores were correlated with impaired contrast sensitivity in the general route analysis, but also with poorer visual acuity during the Google Maps task. These results suggest that the role of peripheral vision on driving performance is complex. Peripheral defocus may disrupt the visual input coming from the periphery, where we can obtain information of the layout, signs, cars changing lanes, pedestrians or other approaching vehicles, and imminent hazards to which it is crucial to react in time. Despite the visual acuity test being the standardized visual test in driver's assessment, contrast sensitivity has shown to be more sensitive to detect visually impaired drivers. Literature about vision and driving has highlighted this visual test as important for tasks such as road signs detection, lane keeping, steering control, etc. [27,39,61,62]. Notwithstanding, it is not surprising to have found an association between poorer visual acuity and poorer driving performance for the Google Maps section, as this secondary task requires good resolution to be able to type and read the desired address. In this line, previous on-road studies have found that impaired visual acuity results in worse signs recognition and road hazard avoidance [63,64].

There are several interventions that can result in changes on peripheral refraction. In pseudophakic eyes at 30°, eyes implanted with monofocal IOLs have 1.5 D of additional astigmatism compared to phakic eyes [25]. More recently, it has been found for pseudophakic eyes even large amounts of astigmatism (around -6D higher astigmatism than in normal eyes) at 45° of eccentricity, affecting visual performance with significant reductions in the peripheral contrast sensitivity [65]. According to our results, such alterations in peripheral contrast sensitivity may compromise the ability to drive a vehicle, with important implications for safety. Given the importance of such alterations, new IOLs design solutions are emerging to address this issue. These lenses are showing promising results, reducing peripheral astigmatism and improving contrast sensitivity compared to standard IOLs [26]. Future research should explore how patients implanted with this new IOL could improve the performance of daily tasks, such as driving.

On the other hand, there are interventions that involve alterations in peripheral visual quality and are commonly applied in patients that can be young inexperienced drivers. An example are the different methods employed for myopia control. Optical treatments employed for this purpose are based on inducing peripheral myopic defocus, such as corneal reshaping by overnight orthokeratology (OK) [32]. It has been found that OK is able to invert the pattern of peripheral refraction, with myopia reductions in the central 25° of visual field, and a myopic shift beyond the 25°. Thus, authors have found that the change in peripheral refraction (spherical equivalent) at 30° and 35° changed with a relationship 1:1 with the baseline spherical equivalent refraction to correct [41]. These results along with ours suggest that patients with moderate to high myopia could have induced peripheral refractive errors that would affect driving performance. Soft contact lenses for myopia control work in a similar way, with designs that incorporate radial refractive gradient. Pauné et al. [66] found a relative peripheral refraction of about -1.5D at 30° (temporal) with this type of lens. One of the newest treatments for myopia control is the defocus incorporated multiple segments (DIMS) spectacle lens. These lenses have a central optical zone for distance vision correction, and a mid-peripheral zone plenty of small circular segments with a relative positive power of +3.5D equally distributed, leading to myopic peripheral defocus [67].

Some limitations need to be considered when interpreting the results presented here. Firstly, individual differences in peripheral refraction may have influenced the results in some extent. Induced peripheral refractive errors may have been partially correcting intrinsic refractive error in some cases, thus decreasing the negative effect found in driving. Despite this, since we used a sample with low central refractive error [35,68], we found significant differences in visual function and a relationship with driving performance. Future studies should measure peripheral refraction of the subjects, in order to homogenize the baseline condition as much as possible and thus study if the effect on driving of the induced refractive errors is more noticeable. Secondly, the design of the lenses required participants to move their head to fixate the secondary task rather than merely make an eye movement. Although in driving it is very common to combine head and gaze movements to scan the environment [69], this could be more time consuming, and could influence the results to some extent. Future studies should induce peripheral refractive errors with contact lenses, thus allowing participants to direct their gaze without moving their head.

To the author's knowledge, there is no previous information about consequences of the induced changes in peripheral refraction in driving performance. Future studies should explore the influence of peripheral defocus in populations with interventions that promote a detriment in peripheral vision such as patients implanted with different IOLs or subjects under myopia control treatments.

5. Conclusions

We have shown that induced peripheral refractive errors may negatively impact driving when performing visual-manual secondary tasks similar to those frequently performed in real driving. Participants in this study demonstrated poorer lane keeping performance, mainly for the 4D of myopic defocus and the +4D of astigmatism. The impairment generated in driving performance was associated with poorer peripheral contrast sensitivity for the route in general, but also with worse visual acuity when subjects were driving and searching an address on Google Maps. These results have implications for subjects whose peripheral refraction is deteriorated by several interventions (cataract surgery, myopia control treatments, etc.). In such circumstances their visual ability for driving could be deteriorated, supposing a risk for their safety. Further studies are needed in order to obtain more information on this aspect and to inform the patients of the possible consequences of peripheral visual changes.

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