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The influence of peripheral vision on driving performance in patients implanted with an inverted meniscus intraocular lens

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The purpose was to analyze and compare the influence of peripheral vision on driving while performing secondary visual-manual tasks in patients implanted with two types of intraocular lenses (IOLs): a standard monofocal IOL and a new inverted meniscus intraocular lens (ArtIOL). This study included 17 participants implanted binocularly with a standard monofocal IOL (control group) and 15 participants implanted binocularly with the ArtIOL. Visual acuity and contrast sensitivity were tested at 40 deg of eccentricity. Driving performance was assessed using a driving simulator. At some points of the route, participants were asked to perform a secondary task while driving. Among other driving variables, self-regulation of driving speed and was analyzed, and the overall driving performance score (ODPS) was calculated. The ArtIOL's group had better peripheral contrast sensitivity (p = 0.003); however, no differences were observed in peripheral visual acuity. Regarding driving performance, no significant differences were observed in the ODPS between the two groups. In the general route, participants implanted with ArtIOLs drove faster, particularly in the mountain road (p = 0.002). The ArtIOL's group self-regulated more for speed, particularly when the characteristics of the road were less complex (p = 0.037). An association was found between better contrast sensitivity and more positive values of the speed adaptation (rho = 0.342; p = 0.006). Thus, participants implanted with the ArtIOLs did not show a significant improvement in driving performance, but had a better contrast in the periphery that contributed to an increased self-confidence while driving.

Keywords Cataract surgery, Pseudophakic patients, Intraocular lens, Peripheral vision, Driving performance, Speed management

The implantation of monofocal intraocular lenses (IOLs) has allowed the recovery of a good visual quality in central vision, similar to that of people who still have a functional and healthy crystalline lens[1]. The typical optical design of these IOLs is biconvex with aspheric surfaces, intended for reducing total spherical aberration and providing the necessary refractive power in foveal vision[2,3]. Thus, in the traditional design of an IOL, peripheral optical quality has been often neglected.

However, optical quality in the peripheral visual field may have an impact on the quality of life of patients, since peripheral vision is necessary to guide search[4], identify objects, and to detect motion and orientation[5]. Peripheral vision corresponds to an eccentricity over 5°–10°, depending on the foveal area considered[6]. Larson and Loschky showed that off-axis performance (beyond 5 degrees of eccentricity) is more useful for categorizing a scene at a basic level than central vision[7]. This makes peripheral vision essential for performing daily tasks like walking, driving, or sports.

Driving is the primary means of autonomous transport in most countries, and perhaps one of the most visually demanding tasks, as it involves the continuous integration of information in a dynamic environment[8]. It is known that peripheral vision is important for driving, especially for recognizing road marks and signals, or detecting road hazards[9]. In this line, some authors stated that impaired off-axis at performance is strongly related to a higher crash risk[10]. Most of these works focus on the useful field of view, which comprises around

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15°–20°[11]. However, according to some authors, peripheral vision is much more extensive and should not be limited only to the useful field of vision when it comes to driving[12] Induced refractive errors in peripheral retina impair driving performance. It has been found that astigmatism and myopic defocus of 4D have a negative impact on driving performance;[13] however, ArtIOLs reduce the peripheral refractive error approximately 2D less defocus and 1D less J0 at 40 deg eccentricity. Thus, the ArtIOL could provide a better peripheral visual acuity and contrast sensitivity, and these benefits may have an influence on driving performance. Current cars incorporate sophisticated in-vehicle navigation systems that enable the control of multiple functions while driving such as calls, music, or messages. However, dual tasking may also jeopardize driving safety, especially when the secondary task is visual-manual[14,15]. In these circumstances peripheral vision becomes even more relevant because drivers have to use it to control the road while paying attention to a secondary task. Furthermore, when engaging in dual tasks, drivers usually adopt some behavioral adaptations to compensate for this complex situation. These adaptations are considered as self-regulation for secondary task demand[16]. In the case of visual impairment, drivers tend to reduce further their speed, as it gives them more time to integrate visual information[17].

Such integration of visual information may be compromised in patients undergoing cataract surgery with standard biconvex monofocal lOLs. In this sense, a recent study has revealed that pseudophakic patients present defects (in terms of deviation in the shape of the hill of vision, peripheral refraction and aberrations) in the peripheral visual field following cataract surgery with all standard IOLs[18]. Peripheral astigmatism is considerably higher in pseudophakic patients compared to normal eyes[2]. According to Venkataraman et al.[19], peripheral refractive errors present in pseudophakic patients implanted with standard monofocal IOLs present a poorer driving-related hazard detection compared with phakic patients. In order to solve these issues, new intraocular lens designs are emerging with the aim of improving peripheral functional vision. The ArtIOLs (Voptica SL, Murcia, Spain) are a new type of intraocular lens with an inverted meniscus shape that has shown to reduce peripheral astigmatism, improving contrast detection with respect to standard monofocal IOLs[20]. As suggested by some authors, this improvement in the peripheral optics of the eye could result in an advantage when accomplishing tasks that require good peripheral visual performance, such as driving[13,19].

Therefore, the aim of this study was to compare peripheral visual quality and its impact on driving when performing secondary visual-manual tasks in patients implanted with a standard monofocal IOL and patients implanted with the new inverted meniscus intraocular lens that enhance peripheral vision (ArtIOLs).

Methods
Participants
A total of 32 pseudophakic participants (26 males/6 females) took part in this study, divided into two groups according to the type of lens implanted before: a control group of patients implanted binocularly with standard monofocal IOLs ($N = 17$; mean age 67.5 ± 7.3 years) and a group of patients implanted binocularly with ArtIOLs ($N = 15$; mean age 66.9 ± 5.1 years). The sample size was selected according to an a priori power analysis and also based on a previous study[21]. No significant age differences were observed between groups ($t(30) = -0.860$; $p = 0.390$). Inclusion criteria comprised not suffering from other ocular pathologies, not consuming drugs that could affect vision, and being a regular driver (drive at least once a week) with a valid driving license. All the procedures described in this study were prospectively approved by the University of Granada Ethics Research Committee (2610/CEIH/2022) and an informed consent was obtained from all participants according to the tenets of the Declaration of Helsinki.

IOLs and surgery
The IOL implanted in the control group was an Asqelio™ Monofocal hydrophobic IOL (QLIO130C). The other group was implanted with ArtIOLs (Voptica SL, Murcia, Spain). These lenses present an inverted meniscus design that improves off-axis optical quality and peripheral contrast sensitivity detection. Figure 1 shows an example of a ray-tracing simulation for an on-axis object and an off-axis object through an ArtIOL compared with a standard biconvex IOL. Both ArtIOLs and control IOLs were implanted using standard surgical techniques for phacoemulsification extracapsular-type cataract extraction.

Driving simulator
For the assessment of driving performance, a fixed-base driving simulator was employed (SIMAX DRIVING SIMULATOR v4.0.8. BETA, SimaxVirt, Pamplona, Spain)[14]. Participants completed a 9.2 km route with two

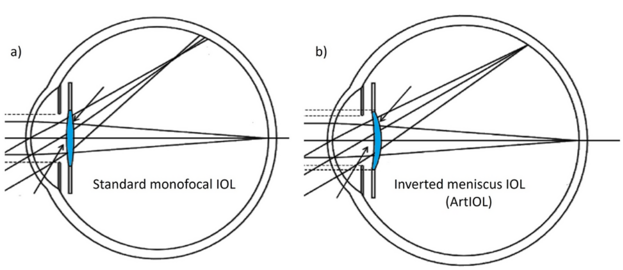

Fig. 1. Ray-tracing for a peripheral object and a central object through an eye implanted with a standard monofocal IOL (**a**) and the ArtIOL (**b**).

different scenarios: a 4.5 km dual carriageway with two lanes in each direction, 120 km/h speed limit (SL), and mainly straight layout, and a 4.7 km mountain road with one lane in each direction, 40 and 90 km/h SL and a winding layout.

The driving variables obtained were: mean speed (km/h), mean time taken to complete the section (s), total distance driven outside the lane (m), a measure of vehicle control that quantifies lane weaving known as standard deviation of the lateral position (SDLP, m)[22], standard deviation (SD) of the angular velocity of the steering wheel (rad/s), which provides information the control of the vehicle and aggressive driving, and total number of collisions. Generally, the time taken to complete the route depends directly on the mean speed and consequently, a higher speed usually results in a shorter time taken to complete the task. However, there are also other factors that may influence in the time taken to complete the route, as is the case of brake or clutch events and collisions along the route. Thus, both variables (mean speed and the time taken to complete the route) were included in the analysis. The overall driving performance score (ODPS) was calculated by averaging the z-scores of the driving variables included in the study, assigning equal weighting to all variables[13,23]. Less negative or more positive values of the ODPS indicate better driving performance. The self-regulation of speed was evaluated by means of the speed adaptation (km/h), calculated as the difference between the SL and the driving speed, in such a way that positive values indicate that the driving speed was below the SL. This parameter help us know how drivers adapt to the SL (i.e., how they self-regulate for speed), indicating if they feel more confident when driving in a road scenario with specific characteristics[16].

Procedure and secondary task

Participants underwent three sessions: two training sessions with the driving simulator and the experimental session. In the training sessions, participants had to drive a route similar to that driven in the experimental session, in such a way that all of them felt familiar and comfortable with the operation of the simulator. At some points of the route, participants were asked to perform a visual-manual secondary task while driving. For that, a 10″ touch screen was used, simulating a navigation system located at 40 deg to the right of the driver. The selection was based on previous studies[13,24] and followed the safety guidelines for in-vehicle information systems purposed by different agencies[25,26]. Drivers had to be 74 cm away from the simulator's front display; however, in some cases, this distance had to be adjusted to enable a comfortable driving and thus, the eccentricity of the secondary task's screen could vary slightly[13]. The setup is represented in Fig. 2.

Participants received a verbal instruction from the examiner when the secondary task started. They were instructed to accomplish the task as soon as possible, but always prioritizing the main task, i.e. driving. Two different secondary tasks were performed: a road sign search task and a Google Maps task. The first consisted of scrolling through a document to search for and identify a specific traffic sign among 10 different signs included in the document. The detail of the road signs subtended 1 arcmin. The Google Maps task consisted of typing a given address on Google Maps. All participants completed the different secondary tasks. The characteristics of each scenario and the secondary tasks performed are shown in Fig. 3.

Visual assessment

Peripheral visual acuity and peripheral contrast sensitivity were tested binocularly at a retinal eccentricity of 40 deg (the same used for the secondary task) under photopic lighting conditions. For that, the Bueno-Matilla vision unit (UBM) (Optonet Ltd, Warrington, Cheshire, UK) was used in the touch screen located at 58 cm[13]. The UBM is a CE certified medical device for Class I visual examination (https://optonet.es/)[27]. For the assessment of the peripheral visual acuity (VA), the test of symmetrical letters was employed (logMAR notation) varying in size with a reduction factor of 1.26. Each letter was presented in isolation, and participants had to respond correctly to at least 2 of 3 presentations for each VA level.

Peripheral contrast sensitivity (CS) was evaluated with isolated letters of an equivalent visual acuity of 0.025 (decimal notation). This size was chosen because participants were able to recognize the letters with comfort at

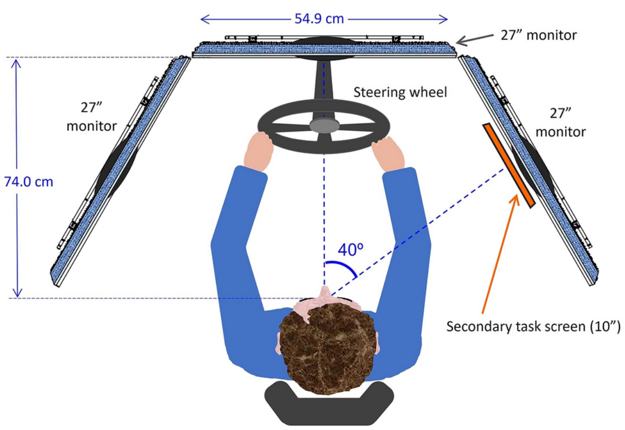

Fig. 2. Experimental setup of the driving task.

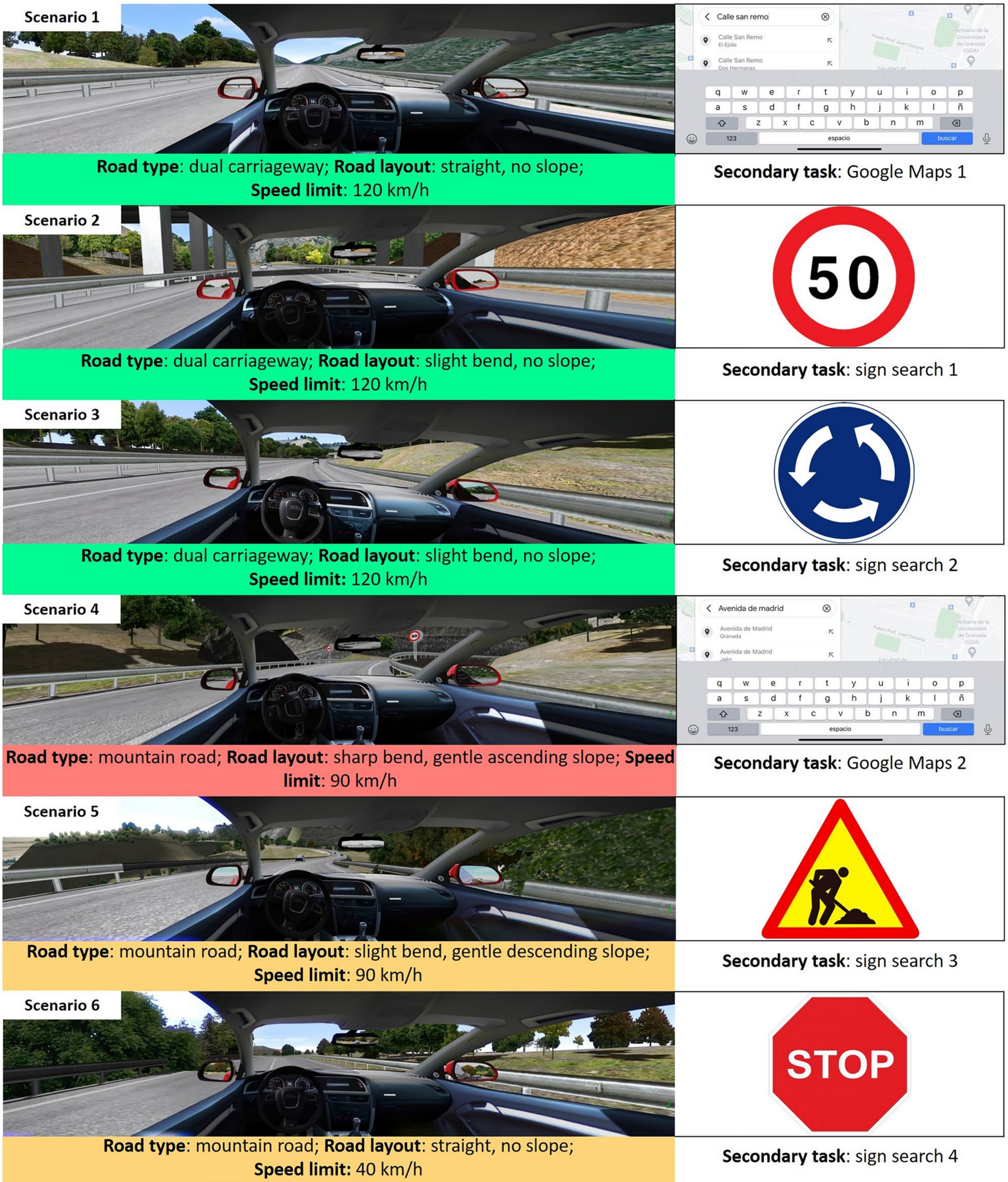

Fig. 3. Characteristics of each scenario and the secondary task performed in each one.

a maximum contrast (100%). The contrast level varied from 100% (0.0 log units) to 0.5% (2.3 log units) in 0.15 log units' steps.

Thus, from now on, when we refer to peripheral vision, we will mean off-axis vision (visual acuity and/or contrast sensitivity) at 40 deg eccentricity.

Statistical analysis

For sample size estimation, an a priori power analysis was performed using the software G*Power 3.1.9.7[28]. According to this analysis, the required sample size to achieve 95% power for detecting an effect at significance level of 0.05 was 15 participants for each group in the case of peripheral contrast sensitivity, and less for the visual acuity and the ODPS (6 and 11 for each group, respectively). The software SPSS V.26 (SPSS Inc., Chicago, IL, USA) was used to perform the statistical analysis of the results. The normality of the data was tested with the Shapiro–Wilk test. To compare demographic, visual, and driving variables in both groups (control vs. ArtIOL), a t-test for independent samples was performed when data were normally distributed. When normality could not be assumed, the Mann–Whitney U test was performed. The 95% confidence intervals were also calculated; in the case of non-normally distributed data, the Hodges-Lehman median difference was applied. Finally, the association between driving and visual performance results was tested with a bivariate correlation analysis (Spearman correlation). Data were analyzed for the whole route (9.2 km), and for the segments corresponding to the Google Maps tasks separately, as this task was more visually demanding. The significance level was set at 0.05).

Results

Peripheral visual function

The mean peripheral VA in control group (logMAR notation) was 1.18 ± 0.22, and 1.17 ± 0.15 for the ArtIOL group. Thus, no statistically significant differences in peripheral VA were observed between the two groups ($t(30) = -0.421$; $p = 0.674$). The mean peripheral contrast sensitivity (logCS) was 0.65 ± 0.39 and 1.04 ± 0.17 in control and ArtIOL groups, respectively. This indicates that participants in the control group were able to detect approximately 22.4% contrast, while participants in the ArtIOL group detected 9.12% contrast, thus demonstrating a better peripheral contrast sensitivity ($t(30) = -2.936$; $p = 0.003$).

Driving performance: general route

Driving performance results of the general route are shown in Table 1. In the dual carriageway, the mean speed was higher for the ArtIOL group. Similarly, in the mountain road, mean speed was significantly higher for this group, and the mean time taken to complete the route was also significantly lower. Also, the control group had more collisions in the mountain road (106.7% higher), although the difference was not statistically significant. As indicated by the higher value of the ODPS, the ArtIOL group drove better in general than the control group, but not significantly.

Driving performance: Google Maps task

The results obtained when participants were interacting with the Google Maps task are presented in Table 2. In the dual carriageway, mean speed was significantly higher in the ArtIOL group. In the mountain road, the mean time taken to complete the route was significantly lower in the ArtIOL group. The control group had more collisions than the ArtIOL group in the dual carriageway and the mountain road (57.2% and 161.1% higher, respectively), although according to the pairwise comparisons and the confidence intervals, this difference was not statistically significant, and the same was observed for the rest of the variables analyzed (Table 2). Thus, the results showed a higher mean ODPS in the ArtIOL while performing the Google Maps task, but difference with respect to the control group were not significant.

Driver self-regulation: speed adaptation

Figure 4 represents the speed adaptation for the control and ArtIOL groups in general (dual carriageway and mountain road) and in each road scenario. In general, participants drove further below the speed limit (SL) in the dual carriageway (120 km/h). In this road section, the ArtIOL group drove closer to the SL. In the mountain road, participants also drove below the SL, but not as much as in the dual carriageway. In both dual carriageway

		Control group	ArtIOL group	Statistic (t/Z)	p-value	95% Confidence interval
Dual Carriageway	Mean Speed (km/h)	71.38 ± 14.89	80.69 ± 16.46	− 1.680	0.052	[− 20.626, 2.007]
	Mean time (s)[a]	222.74 ± 49.18	198.43 ± 55.07	− 1.643	0.100	[− 3.696, 58.312]
	Total distance driven outside the lane (m)	604.65 ± 458.92	560.55 ± 352.20	0.302	0.382	[− 254.373, 342.589]
	SD angular velocity of the steering wheel (rad/s)[a]	0.36 ± 0.18	0.36 ± 0.16	− 0.397	0.710	[− 0.116, 0.115]
	SDLP (m)	0.73 ± 0.25	0.74 ± 0.22	− 0.128	0.449	[− 0.180, 0.159]
	Collisions[a]	0.24 ± 0.44	0.27 ± 0.46	− 0.201	0.840	[0.000, 0.000]
Mountain Road	Mean Speed (km/h)	45.54 ± 6.85	53.17 ± 6.77	− 3.162	0.002*	[− 12.566, − 2.703]
	Mean time (s)[a]	346.94 ± 146.13	321.45 ± 55.93	− 2.134	0.033*	[24.515, 101.815]
	Total distance driven outside the lane (m)	854.82 ± 580.63	822.25 ± 261.31	0.197	0.422	[− 302.423, 366.987]
	SD angular velocity of the steering wheel (rad/s)	0.73 ± 0.34	0.70 ± 0.26	0.305	0.381	[− 0.187, − 0.252]
	SDLP (m)	0.77 ± 0.14	0.76 ± 0.12	0.337	0.369	[− 0.079, 0.111]
	Collisions[a]	1.24 ± 1.26	0.60 ± 0.74	− 1.447	0.148	[0.000, 1.000]
ODPS		− 0.16 ± 0.69	− 0.004 ± 0.484	0.652	0.260	[− 0.301, 0.583]

Table 1. Driving performance in the general route (dual carriageway and mountain road) (mean value ± SD). *Statistical significance ($p < 0.05$). [a]Non-parametric test applied. ODPS = Overall driving performance score; SD = standard deviation; SDLP = standard deviation of lateral position. The statistic and the p-value resulting from the comparisons between the two groups (control and ArtIOL) are also included.

		Control group	ArtIOL group	Statistic (t/Z)	p-value	95% Confidence interval
Dual Carriageway	Mean Speed (km/h)	56.66 ± 23.15	73.82 ± 20.83	2.192	0.018*	[− 33.142, − 1.169]
	SD Speed (km/h)	8.42 ± 4.19	8.58 ± 5.56	− 0.092	0.464	[− 3.687, 3.370]
	Mean time (s)	36.45 ± 16.79	29.87 ± 13.71	1.204	0.119	[− 4.580, 17.745]
	Total distance driven outside the lane (m)	170.46 ± 164.98	144.32 ± 117.33	0.510	0.307	[− 78.553, 130.836]
	SD angular velocity of the steering wheel (rad/s)[a]	0.57 ± 0.31	0.49 ± 0.22	− 0.472	0.637	[− 0.117, 0.265]
	SDLP (m)	0.85 ± 0.36	0.83 ± 0.37	0.177	0.430	[− 0.241, 0.286]
	Collisions[a]	0.18 ± 0.39	0.07 ± 0.26	− 0.922	0.356	[0.000, 0.000]
Mountain Road	Mean Speed (km/h)	36.22 ± 14.36	40.09 ± 10.08	− 0.872	0.195	[− 12.949, 5.202]
	SD Speed (km/h)[a]	9.23 ± 6.38	8.27 ± 4.30	− 0.132	0.895	[− 2.742, 2.796]
	Mean time (s)[a]	52.24 ± 34.82	28.90 ± 13.18	− 2.209	0.027*	[1.518, 33.099]
	Total distance driven outside the lane (m)[a]	161.84 ± 144.63	119.23 ± 106.43	− 0.623	0.533	[− 35.737, 137.472]
	SD angular velocity of the steering wheel (rad/s)[a]	0.88 ± 0.41	0.73 ± 0.26	− 0.548	0.584	[− 0.113, 0.336]
	SDLP (m)[a]	0.68 ± 0.19	0.65 ± 0.21	− 0.548	0.584	[− 0.112, 0.153]
	Collisions[a]	0.65 ± 0.21	0.18 ± 0.53	− 1.350	0.177	[0.000, 0.000]
ODPS		− 0.11 ± 0.57	0.14 ± 0.43	1.378	0.089	[− 0.119, 0.613]

Table 2. Driving results in the segments corresponding to the Google Maps task in the dual carriageway and the mountain road (mean value ± SD). The statistic and the p-value resulting from the comparisons between the two groups (control and ArtIOL) are also included. *Statistical significance ($p < 0.05$). [a]Non-parametric test applied. ODPS = Overall driving performance score; SD = standard deviation; SDLP = standard deviation of lateral position.

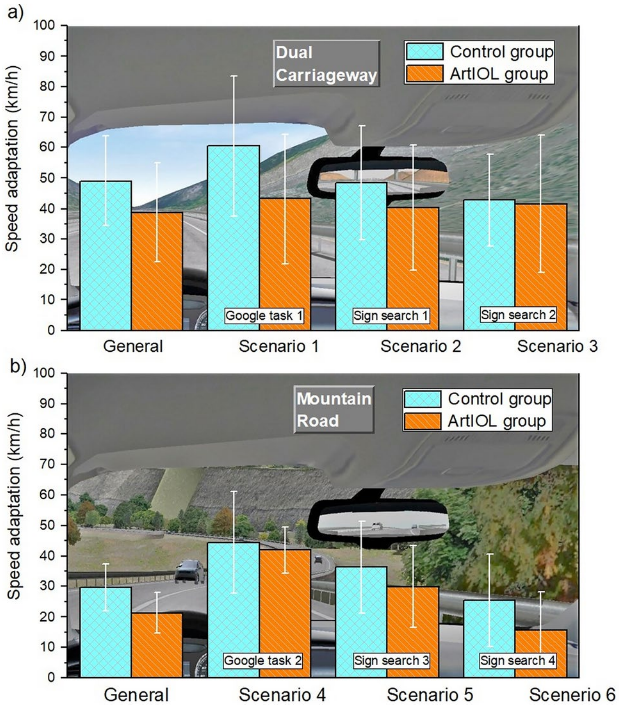

Fig. 4. Speed adaptation in dual carriageway (**a**) and mountain road (**b**) for the general route and the different tasks separately.

and mountain road, the ArtIOL group drove closer to the SL (i.e., faster) than the control group ($Z = 1.869$; $p = 0.062$ and $Z = 3.040$; $p = 0.002$, respectively). When analyzing each scenario separately, it was found that the ArtIOL group self-regulated their driving speed less while performing the secondary tasks. However, differences were significant only for scenario 1 ($Z = 2.096$; $p = 0.037$). These results could indicate that participants implanted with ArtIOLs felt more confident than the control group when driving while performing the secondary task, particularly when the road environment is less complex.

Finally, the correlations analysis showed a positive association between peripheral contrast sensitivity and the speed adaptation (rho = 0.342; p = 0.006), indicating that participants with higher values of contrast sensitivity drove faster.

Discussion

Visual results indicated that there were no significant differences in peripheral visual acuity at 40 deg between the two groups. Differences in peripheral visual acuity depend mainly on the eccentricity at which the VA has been assessed,[29] and also on the refractive error in the periphery[13].

On the other hand, peripheral contrast sensitivity (log CS) was significantly better in the ArtIOL group. It has been reported that contrast sensitivity decrease when inducing different amounts of spherical defocus and astigmatism[13]. Similarly, other authors observed that peripheral contrast detection (40 deg eccentricity) was significantly better in patients implanted with ArtIOLs compared to that of patients implanted with standard monofocal IOLs[20]. According to these authors, this improvement in contrast detection was due to the reduction of the peripheral astigmatism in the ArtIOL group thanks to the new optical design of these lenses. Peripheral astigmatism leads to a decrease of the optical quality in the periphery, contributing to the deterioration of the contrast sensitivity[30]. Notwithstanding, as stated before, visual acuity was quite similar in both groups at 40 deg. That could be explained by the fact that peripheral retina is more sensitive to detection tasks than resolution tasks. Indeed, it has been found that the correction of the peripheral optics of the eye have a limited impact on the resolution acuity, but may have a greater impact on other aspects such as contrast[29,31].

With regard to driving performance, the results obtained in both groups indicated that, in the general route, patients implanted with ArtIOLs drove faster than the control group. When analyzing driving performance in the segments corresponding to the Google Maps tasks, similar results were obtained regarding mean speed. Nevertheless, both groups reduced their speed when driving while interacting with the touch screen. It has been suggested that, although patients increase their driving frequency after cataracts surgery, such habits may be altered dependending on the optical design and the material of the IOL implanted, as these characteristics have an influence on the contrast sensitivity and disability glare[32]. On the other hand, some authors have reported that drivers slowed down their speed as a self-regulation mechanism when they feel less confident, e.g. when texting[33–35] or when their vision is impaired. In this sense, it has been stated that patients with cataracts drive slower than the traffic flow[36]. It is noteworthy that participants in the control group had twice the number of collisions than the ArtIOL group, particularly when performing the Google Maps task, which is more visually demanding than the road sign search task.

Speed self-regulation was evaluated by obtaining the speed adaptation, which provides information about how drivers adapt their driving speed to the speed limit (SL) established. Results showed that the ArtIOL group self-regulated less their speed in both scenarios, but in a greater extent in the dual carriageway. The increased workload that involves the interaction with a digital device, like a smartphone or a navigation screen, leads to a reduction of the speed. Therefore, drivers who reduce their speed when interacting with the device are aware of this increased workload and try to compensate for it[15]. Also, it should be noted that visual demand increases when using a device while driving, and therefore the driver's resources have to be shared by both tasks. Thus, drivers with a more impaired peripheral vision, might experience an increase of the workload when performing this dual task, which would explain the results obtained.

When analyzing the segments corresponding to each secondary task separately, we observed that differences in mean speed between the two groups (control and ArtIOL) were more remarkable in the scenarios corresponding to the straight segments in both dual carriageway (Google Maps task, SL 120 km/h) and mountain road (signal search task, SL 40 km/h). However, in scenario 1 (Google Maps task, SL 120 km/h), participants in both groups slowed down more than in the other scenarios. Two conclusions can be drawn from these findings: the first is that participants in both groups self-regulated less for speed when the secondary task was easier, and the second is that the ArtIOL group felt more confident than the control group when accomplishing the secondary task, particularly when the road was less complex, i.e. in the straight segments. In the same line, previous studies observed that curved roads caused more insecurity, leading to a further reduction of the speed[37,38].

Despite the variability observed in speed management, it is noteworthy that the ODPS, i.e. the variable that provides general information on driving performance, did not show significant differences between the two groups. This could be explained by different reasons. First, according to the literature, peripheral astigmatism is close to -4D in pseudophakic patients. However, ArtIOLs only provide a partial compensation (-2D approximately), so differences in driving performance, which is a highly variable task depending on many factors, would be less than expected if peripheral improvement was greater[13,20]. Second, the ODPS was calculated considering all driving variables; however, peripheral vision does not have the same weight in all of them. Driving speed is one of the most sensitive variables to changes in peripheral vision, as one of the main compesatory techniques in patients with peripheral loss is a reduction in speed, along with an increase of fixations and scanning[39,40]. Also, it should be noted that, although the results obtained in the power analysis indicated that the sample size included in this study would be enough to observe an effect on the ODPS, the variability of the driving results considering the whole sample, as shown by the amplitude of the 95% confidence intervals and the standard deviations obtained (Tables 1 and 2) is quite high. This variablity in driving performance between subjects has been observed before in a previous work under similar conditions,[13] and yet the sample size in that study was larger. Thus, we can conclude that, despite the results of the power analysis, the sample size should have been larger to show an effect on driving performance.

The results obtained in this study point toward a better peripheral contrast sensitivity as a possible cause for the increased self-confidence when driving while performing a secondary task, as indicated by the higher driving speed in the ArtIOL group with respect to the control group. Indeed, we observed that participants who self-regulated less their speed also had a better peripheral contrast sensitivity. According to Henderson et al.[41], peripheral contrast thresholds have been associated to a higher accident risk. In this sense, it has been shown that self-reported driving difficulty following cataract surgery seems to be more related to the enhanced contrast sensitivity in the operated eye than to visual acuity[42]. It has also been stated that peripheral vision is quite important for maintaining the car in the center of the lane[9,43]. For that, the peripheral contrast is essential, since it enables to distinguish the marks delimiting the lane on the road. Notwithstanding, we obtained similar values of the SDLP in both groups, but it might be attributed to the high contrast of the roadmarks in the driving simulator. In a real situation, these marks would probably not present such a high contrast due to wear, and therefore differences might be higher. Moreover, peripheral vision is not only important for drivers, but also for pedestrians, who use their peripheral vision to guide their feet. Some authors have stated that peripheral contrast also plays an important role when walking or cycling, particularly in unpredictable and unfavorable environments[9].

It should also be noted that the driving results reported in this study were obtained from participants implanted binocularly. However, between the first and the second cataract surgery, participants are implanted monocularly. The interocular differences resulting from this condition may negatively affect binocular vision,[44,45] posing a risk to driving. On the other hand, a limitation of this study is that the driving style and habits of the drivers were not considered, which could influence the results. However, the driving frequency was similar for most participants and, considering that all of them had to train to learn to use the driving simulator, they were all in similar conditions at the time they completed the experimental session. Also, it should be noted that the peripheral refraction could not be assessed in this study, which represents a limitation since the real peripheral defocus induced by the IOLs in each individual depends on the peripheral refractive error. Thus, the results obtained should be interpreted with caution.

In conclusion, the enhanced peripheral contrast in drivers implanted with ArtIOLs could provide a higher confidence when driving in general, and particularly while performing a secondary task. This is important for the elderly, as it gives them autonomy and contributes to their quality of life. On the other hand , no differences were observed in the overall driving performance, so it is not clear whether ArtIOls would represent a real benfit for pseudophakic drivers. In this sense, further research would be necessary to analyze whether the influence of other factors on driver's self-regulation mechanisms following cataract surgery would be involved in the changes observed on driving speed. It would also be interesting to analyze the outcomes of these new intraocular lens designs and their possible benefits on other daily tasks to better understand how the enhanced peripheral optics in these intraocular lenses would constitute an improvement in the quality of life of pseudophakic patients.

Data availability

Data will be available from the corresponding author on reasonable request.

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Conceptualization (S.O.P., M.C.L., R.G.A., P.A.); data curation (M.C.L., S.O.P.,C.R., L.H., E.A.); surgeries and clinical consueling (J.M.); formal analysis (M.C.L., S.O.P., J.J.C.T., C.R., L.H., E.A., J.M., P.A.); tables and figures preparation (M.C.L.); Funding acqisition (R.G.A., J.J.C.T., P.A.); Supervision (R.G.A., J.M., P.A.); Writing the main manuscript (M.C.L., R.G.A., P.A.); Review & editing (All authors).

Declarations

Competing interests

Dr. Artal holds patents on the meniscus IOLs. Dr. Robles and Dr. Hervella are employees of Voptica S.L. The remaining authors have no financial or propietary interest in the materials presented herein.

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