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ORIGINAL ARTICLE

Identifying Absolute Preferred Retinal Locations during Binocular Viewing

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ABSTRACT

Purpose. We present a new method for identifying the absolute location (i.e., relative to the optic disc) of the preferred retinal location (PRL) simultaneously for the two eyes of patients with central vision loss. For this, we used a binocular eye-tracking system that determines the pupillary axes of both eyes without a user calibration routine.

Methods. During monocular viewing, we measured the pupillary axis and the angle between it and the visual axis (angle Kappa) for 10 eyes with normal vision. We also determined their fovea location relative to the middle of the optic disc with the MP-1 microperimeter. Then, we created a transformation between the eye-tracking and microperimeter measurements. We used this transformation to predict the absolute location of the monocular and binocular PRLs of nine patients with central vision loss. The accuracy of the monocular prediction was evaluated with the microperimeter. The binocular PRLs were checked for retinal correspondence and functionality by placing them on fundus photographs.

Results. The transformation yielded an average error for the monocular measures of 0.2 (95% confidence interval, 1.0 to −0.6 degrees) horizontally and 0.5 (95% confidence interval, 1.1 to −0.1 degrees) vertically. The predicted binocular measures showed that the PRLs were generally in corresponding locations in the two eyes. One patient whose PRLs were not in corresponding positions complained about diplopia. For all patients, at least one PRL fell onto functional retina during binocular viewing.

Conclusions. This study shows that measurements of the location of the binocular PRLs relative to the pupillary axes can be transformed into absolute locations.

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Key Words: preferred retinal location, PRL, central vision loss, binocular vision, AMD, binocular fixation

As an adaptive mechanism to the loss of central vision, patients develop preferred retinal locations (PRLs)[1,2] in the eccentric retina. The absolute location of the PRL can be identified with instruments such as the MP-1 (Nidek Technologies Srl, Vigonza, PD, Italy), the MAIA (CenterVue, Padua, PD, Italy), and the Rodenstock scanning laser ophthalmoscope (SLO; Rodenstock GmbH, Munich, Germany; this device is no longer commercially available), or instruments that use a combination of optical coherence tomography and SLO, such as the OPKO OCT-SLO (OPKO, Miami, FL).[3] These instruments, however, record the PRL location in one eye only, which may not be the appropriate data for understanding binocular vision in patients with central vision loss (although an optical attachment for binocular imaging with an SLO has been proposed).[4]

Gaze location refers to the intersection of the visual axis and a plane parallel to the frontal plane of the observer's face. In people with normal retinas, the visual axis is the line connecting the fovea with the center of curvature of the cornea. In people with central vision loss, on the other hand, the visual axis is the line connecting the PRL with the center of curvature of the cornea. The location of the PRL on the retina cannot be inferred directly from the output of most conventional eye-trackers. Gaze position may be different when viewing changes from monocular to binocular[5] or vice versa,[6] but such changes can only be interpreted as changes in the relative location of the PRL, its absolute location on the retina remaining unknown.

The absolute location of the PRL during binocular viewing could be inferred from the optic disc-to-PRL distance derived from a microperimeter and the gaze position obtained with an eye-tracker. This way of estimating the eccentricity of gaze is based on three assumptions, all of which could be wrong. The first assumption is that the monocular PRL's location measured with the

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microperimeter is the same as that used during monocular viewing when eye position is being measured with the eye-tracker. The second assumption is that the monocular PRL location measured with the microperimeter is the same as that used by patients during binocular viewing. Finally, the third assumption is that the same PRL is used with every calibration point during a calibration procedure.

The pupillary axis is a line that connects the center of the pupil with the center of curvature of the cornea. It intersects the retina away from the fovea at an angle Kappa with its vertical (Kappa$_y$) and horizontal (Kappa$_x$) components. In cases in which the PRL changes, the estimate of the pupillary axis remains the same whereas angle Kappa changes to reflect the change in the visual axis (i.e., the new PRL location). Researchers testing patients with central vision loss by means of conventional eye-trackers are faced with the problems of (1) fixation instability during calibration (although this difficulty can be diminished by using appropriate fixation targets[7] and verifying the calibration matrix), but more problematically (2) the fact that conventional calibration routines assume that the participants foveate the targets. To illustrate the problem, if a patient uses one PRL for a calibration and a fixation test and then uses a different PRL to repeat the calibration and the test, a conventional eye-tracker would return identical results for the two tests, and it would be impossible to detect the difference. The system we present estimates the pupillary axis without a user calibration routine.

In this proof-of-principle study, we present a method for determining the absolute location of the PRLs during monocular and binocular viewing. It is based on the fact that by knowing the absolute location of the place where the pupillary axis intersects the retina, we can then establish the absolute location of the PRL by using the horizontal and vertical values of angle Kappa. To do so, we obtained the horizontal and vertical components of the angle Kappa of a group of control subjects with healthy retinas and, knowing their fovea location, determined the absolute location of the place where the pupillary axis intersects the retina. We then used the average values of this control group to determine the absolute location of the visual axis (PRL) of patients with central vision loss. Understanding binocular vision is important for designing optimal rehabilitation methods for patients with central vision damage.

METHODS

Procedures

To determine the absolute location of the PRLs during binocular viewing in patients with central vision loss, two instruments were used: the VISION 2020-RB (El-MAR Inc, Toronto, Ontario, Canada) eye-tracker and the MP-1 microperimeter. The eye-tracking system provides an estimate of the pupillary axes of the eyes without a user calibration procedure and has been described elsewhere.[8–10] Eye positions during fixation of people with normal vision and patients with bilateral central vision loss were recorded monocularly with both the eye-tracker and the microperimeter and binocularly with the eye-tracker. The eye-tracker measured the direction of the pupillary axis and the angle between the PRL (fovea for control subjects) and the pupillary axis in each eye.

The absolute location of the monocular PRL (fovea for the control subjects) relative to the middle of the optic disc was first measured with the microperimeter. Using the monocular measurements of the eye-tracker and the microperimeter of the control subjects, a transformation from eye-tracking measurements to microperimeter measurements was created. This transformation was then used to predict the absolute location of the monocular PRLs in the patients and the accuracy of the prediction confirmed with the values obtained with the microperimeter.

The same transformation was used for measurements of the eye-tracker's PRLs under binocular viewing to obtain the absolute locations of the two PRLs relative to the middle of the optic disc. The details of the transformation are given below.

MP-1 Microperimeter

The MP-1 microperimeter incorporates an automatic eye-tracking system for recording horizontal and vertical eye positions at a sampling rate of 25 Hz. It is particularly suitable for identifying fixation location (i.e., fovea location in control subjects or the PRL location in patients with central vision loss) because its eye-tracking system records eye position relative to an anatomical landmark (i.e., a retinal blood vessel) while compensating for stimulus projection location. The microperimeter can also capture color fundus photographs that typically encompass the macula and the optic disc. Fixation locations can be registered on the color fundus photograph off-line, allowing various measurements to be performed, such as the fovea or PRL's location relative to the middle of the optic disc.

For this study, the fixation stimulus was a 3-degree red cross projected in the middle of the microperimeter's viewing area. Occasionally, the size of the target was enlarged for patients who could not see the cross. Testing was performed in a darkened room, and all participants were instructed to keep their gaze in the middle of the fixation cross, while they kept their head steadied by the chin rest and headrest of the instrument. Fixation recordings were performed three times for each eye, each lasting between 15 and 18 seconds. A color fundus photograph was taken at the end of fixation examination. No mydriatic drops were used. The fovea and PRL locations (horizontal and vertical components) were measured from the middle of the fixation cluster to the middle of the optic disc on the fundus photograph using the radial grid of the microperimeter.[11] The values used were the medians of the three observations of each eye.

Binocular Eye-Tracker

The Vision 2020-RB eye-tracker is a video-based binocular eye-tracking system that requires no user calibration to measure the direction of the pupillary axes. It uses two cameras plus three corneal reflections and the center of the pupil of each eye to estimate its pupillary axes (the line connecting the center of the curvature of the cornea with the center of the pupil) as well as the angle Kappa between the pupillary axis and the visual axis or line of gaze.[10] The eye-tracker's two cameras are mounted on a metallic frame and oriented in such a way that their optic axes intersect at a distance of about 65 cm. The eye-tracker has three screens at viewing distances of 33 cm, 70 cm, and 6 m; the operator can display fixation targets on any of the screens. The eye-tracker calculates angle Kappa from the difference in the direction of the line that connects the fixation target with the center of the curvature of the cornea and the pupillary axis. Estimates of the horizontal ($Kappa_x$) and vertical ($Kappa_y$) components of angle Kappa are obtained at a sampling rate of 30 Hz.

To approximate the testing conditions of the microperimeter, the fixation target for the eye-tracker measurements was presented at 6 m in a darkened room, while participants had their head steadied with a chin rest. The target's size was set so that the participant could see it well with each eye. All participants were instructed to keep their gaze in the middle of the fixation target. They did not wear any correction when performing this task. Data were recorded continuously, monocularly for each eye and binocularly, and were flagged manually for about 15 seconds when subjects confirmed they could see the target. This sequence was repeated three times. Only the flagged data were used for the calculation of the horizontal and vertical components of angle Kappa after blinks and outliers (i.e., data points more than 2 SDs away from the mean) were removed. During monocular recordings, an infrared filter that appeared black to the participants but allowed the eye-tracker to record the eye's position was used as an eye patch.

Eye-Tracker-to-Microperimeter Transformation

To estimate the absolute location of the PRL during binocular viewing, a transformation between the measurements from the

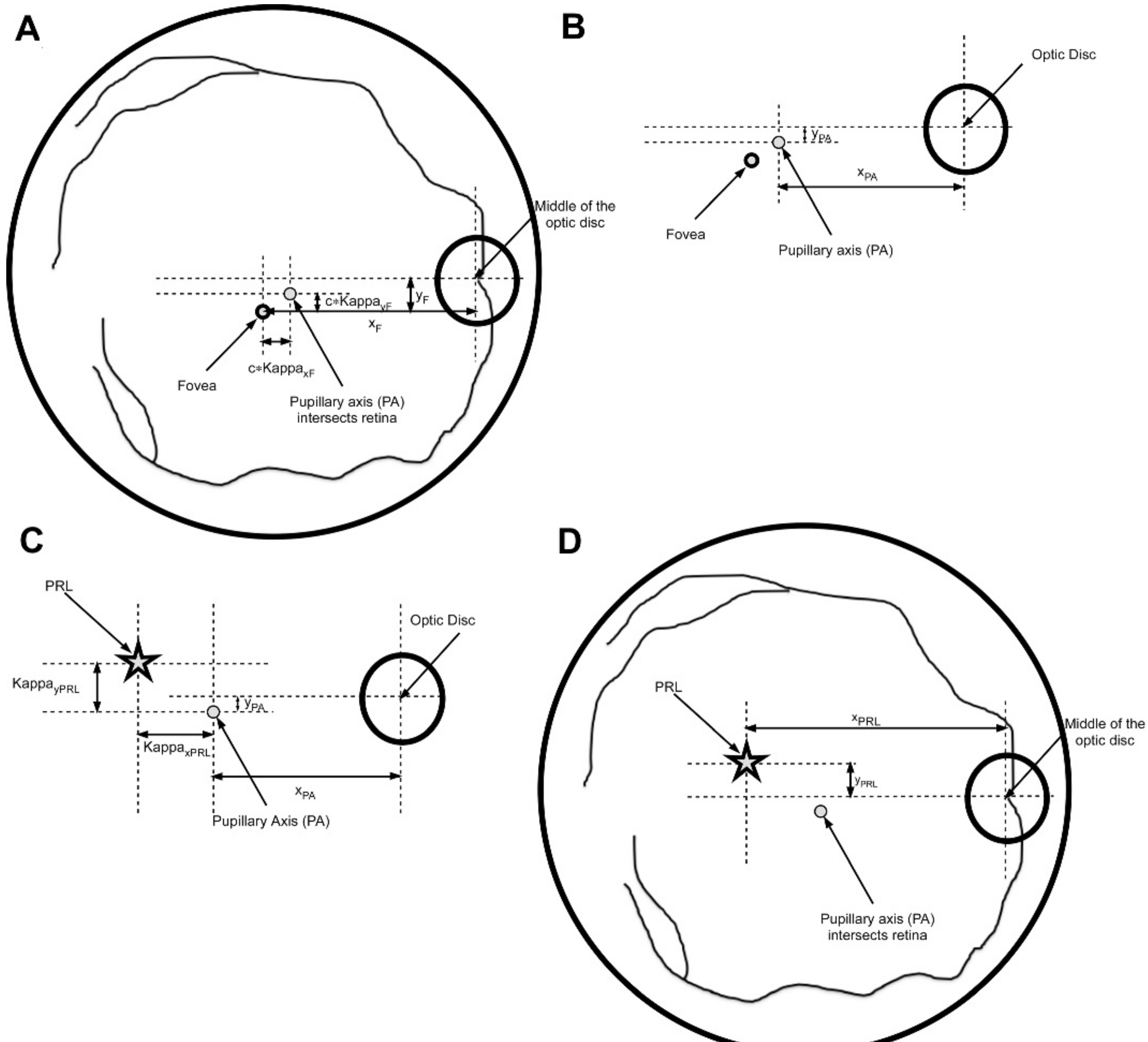


FIGURE 1.

Schematic representation of the eye-tracker to microperimeter data transformation (right eye). (A) For the control subjects, the location of the fovea relative to the middle of optic disc as obtained with the microperimeter and the location of the pupillary axis relative to the fovea as obtained with the eye-tracker (i.e., the components of angle Kappa: $Kappa_{xF}$ and $Kappa_{yF}$, multiplied by the scaling factor *c*) are shown. (B) For the control subjects, the location of the pupillary axis relative to the middle of the optic disc is shown. (C) For the patients, the horizontal and vertical components of angle Kappa ($Kappa_{xPRL}$ and $Kappa_{yPRL}$) as obtained with the eye-tracker are shown. (D) The PRL location (x_{PRL}, y_{PRL}) relative to the middle of the optic disc obtained from the transformation is shown.

two systems during monocular viewing was determined using the following steps:

1) For the control participants:
   a) The horizontal ($Kappa_{xF}$) and vertical ($Kappa_{yF}$) components of angle Kappa were obtained with the eye-tracker during monocular viewing.
   b) The location of the fovea relative to the middle of the optic disc was measured with the microperimeter. The middle of the optic disc was determined on the fundus photographs and then the horizontal (x_F) and vertical (y_F) distances from the fovea to the middle of the optic disc were measured in degrees.
   c) The location where the pupillary axis intersects the retina (x_{PA}, y_{PA}) relative to the center of the optic disc was determined (Fig. 1).
2) For the patients:
   a) The horizontal ($Kappa_{xPRL}$) and vertical ($Kappa_{yPRL}$) components of angle Kappa were obtained with the eye-tracker during monocular viewing.
   b) The location of the monocular PRL relative to the middle of the optic disc was estimated as:

$$x_{PRL} = c * Kappa_{xPRL} + x_{PA}$$

$$y_{PRL} = c * Kappa_{yPRL} + y_{PA}$$

   where c is a scale factor accounting for the fact that the eye-tracker measures visual angles as originating at the center of the curvature of the cornea (nodal point of the eye), whereas the microperimeter measures visual angles from the center of the physical plane of the iris. (This scaling factor has a value $c = 0.817$ to accommodate for the above differences. Its calculation is based on the following formula:

$$c = (C-B)/(P-B),$$

   where $(C - B)$ is the distance between the center of corneal curvature and the posterior pole of the eye [16.09 mm] and $(P - B)$ is the distance between the entrance pupil of the eye and the posterior pole of the eye [19.69 mm].)
   c) The location of the PRL relative to the middle of the optic disc was also obtained with the microperimeter. These locations were compared with the locations obtained from the transformed data (step 2b).
   d) The transformation was then applied to the data recorded binocularly with the eye-tracker. The obtained distances in degrees are illustrated schematically in Fig. 1.

RESULTS

Participants

Clinical and demographic characteristics of the participants are shown in Table 1 including those of five control subjects with normal vision (mean [±SD] age, 45 [±18] years).

Patients

A total of nine patients with bilateral central vision loss (mean [±SD] age, 73 [±16] years) participated. They had no other ocular pathology with the exception of mild cataract and were recruited from the Eye Clinic at the Toronto Western Hospital. The first six of these patients showed a consistent PRL location during repeated testing with the microperimeter (i.e., the three fixation recordings with the microperimeter for each eye showed the same PRL location). They had all participated in other studies in our laboratory and all but one had a history of their two eyes' PRL location obtained with multiple examinations over a period ranging from 2 years to a few days. The data from these patients were used to verify the agreement between the monocular measures with the eye-tracker and the microperimeter.

Of the last three patients (P7 to P9), patient 7 had participated in one of our studies 6 years before, but only data from one eye were recorded at the time. The last two patients shown in Table 1

TABLE 1.
Clinical and demographic characteristics of the participants

ID	Age, y	Sex	Acuity, logMAR OU	OD	OS	Stereoacuity, s	Disease duration, y	Diagnosis
P1	87	F	0.26	1.1	0.3	400	20	AMD
P2	36	M	0.8	0.88	0.88	No stereo	4	Cone dystrophy
P3	69	M	0.62	0.76	0.66	800	15	AMD
P4	63	F	0.14	0.53	0.14	No stereo	3	AMD
P5	79	M	0.36	1.1	0.32	3000	15	AMD
P6	82	M	0.6	1.3	0.64	3000	20	AMD
P7	81	M	1.0	0.88	1.0	No stereo	12	AMD
P8	79	F	0.32	0.58	0.76	3000	3	AMD
P9	87	M	0.9	0.9	1.2	No stereo	14	AMD
C1	54	F	0	0.1	0	40	N/A	Normal
C2	72	M	−0.18	−0.18	−0.18	40	N/A	Normal
C3	25	F	0	0	0	40	N/A	Normal
C4	44	F	−0.26	−0.22	−0.22	40	N/A	Normal
C5	31	F	−0.1	−0.1	−0.1	40	N/A	Normal

AMD, age-related macular degeneration; logMAR, logarithm of the minimum angle of resolution; N/A, not available; F, female; M, male.

TABLE 2.

Absolute location of the PRL measured with the microperimeter and determined with transformed data from the eye-tracker for the monocular viewing condition

	Absolute PRL location with microperimeter, degrees				Absolute PRL location with transformed data from the eye-tracker, degrees			
	OD		OS		OD		OS	
ID	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*
P1	17.2	−1.7	15	−0.3	16.0	−0.8	12.6	−0.9
P2	16.3	0.8	12.8	1.5	16.8	2.8	13.3	2.2
P3	15.8	−7.3	16.3	−6.5	15.8	−6.0	17.2	−6.2
P4	16.2	−1	15	−2.2	16.3	−1.2	15.4	−1.7
P5*	N/A	N/A	16	−4.1	17.5	6.2	18.4	−3.0
P6	16	4.2	14	1.2	16.3	4.3	14.4	0.4

Negative *y* values indicate a PRL location inferior on the retina relative to the center of the optic disc.

*PRL location for the right eye could not be recorded with the microperimeter.

N/A, not available.

(P8 and P9) had not been tested before this study although the three fixation recordings for each eye done with the microperimeter showed a consistent PRL location. The PRL location in the right eye of P5 and in the left eye of P9 could not be recorded with the microperimeter. These patients had very small pupils that, coupled with poor vision and unstable fixation, made it impossible to get a clear image of the fundus and record the PRL location without using mydriatic drops.

All participants gave informed consent, and the research was approved by the University Health Network's Research Ethics Board and conducted in accordance with the tenets of the Declaration of Helsinki.

Fovea Location and Offsets between the Two Systems

For the n = 10 eyes of the control participants, the location of the fovea relative to the optic disc measured with the microperimeter was 15.5 (±1.0) degrees horizontally and −1.6 (±0.9) degrees vertically. These values are in agreement with published data.[11–13] For the same eyes, the horizontal and vertical components of angle Kappa measured with the eye-tracker during monocular viewing were $\text{Kappa}_x = 1.7$ (±0.8) degrees and $\text{Kappa}_y = 0.8$ (±0.7) degrees, respectively. (These values include the scale factor [$c = 0.817$] to account for the difference in the origin of the angular measurements of the two systems.) The location of the pupillary axis relative to the middle of the optic disc was $x_{PA} = 13.8$ degrees and $y_{PA} = -0.8$ degrees.

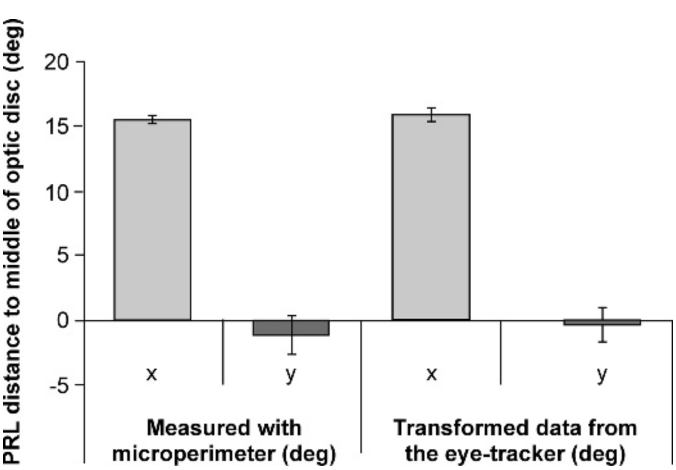


FIGURE 2.

For the monocular viewing conditions, mean absolute location of the PRL measured with the microperimeter and determined with the transformed data from the eye-tracker. Error bars are ±1 SE.

Verifying the Transformation: PRL Location during Monocular Viewing

For the n = 11 eyes of the six patients with a consistent PRL (Table 1), the absolute location of the monocular PRL relative to the middle of the optic disc was measured with the microperimeter. The transformed values from the eye-tracker to the microperimeter system for monocular viewing are shown in Table 2 and the mean values are shown in Fig. 2. The difference between these two measures was computed, yielding an average error of 0.2 (95% confidence interval, 1.0 to −0.6 degrees) horizontally and 0.5 (95% confidence interval, 1.1 to −0.1 degrees) vertically.

Applying the Transformation: PRL Location during Binocular Viewing

The transformation was applied to data recorded with the eye-tracker during binocular viewing for the first six patients. The absolute location of the PRL relative to the middle of the optic disc was recorded simultaneously for the two eyes and is shown in Table 3.

These PRLs were located on the fundus photographs obtained with the microperimeter. Fig. 3 shows data from P2 for whom the monocular and binocular PRLs were very similar. The binocular PRLs fall on functional retina and in corresponding positions in the two eyes. This similarity can be appreciated in the eye movement traces: When the viewing condition changed from monocular

TABLE 3.

Absolute location of the PRL relative to the middle of the optic disc recorded simultaneously for the two eyes

	Absolute PRL location with transformed data from the eye-tracker, degrees			
	OD		OS	
ID	*x*	*y*	*x*	*y*
P1	15.1	−0.1	12.2	−1.0
P2	16.7	3.2	12.7	2.7
P3	14.8	−5.5	17.8	−6.8
P4	16.0	−1.2	15.2	−1.4
P5*	19.6	−2.5	18.3	−3.0
P6	16.1	1.2	14.7	0.0

Negative *y* values indicate a PRL location inferior on the retina relative to the center of the optic disc.

*P5 complained of diplopia during binocular viewing recordings.

(right eye viewing) to binocular and then back to monocular (left eye viewing), there was no obvious shift. Fig. 4 shows data from P6 whose monocular PRL in the worse eye changed location during binocular viewing, falling on the scotoma but in a corresponding position with the PRL of the better eye. This change can also be appreciated in the eye movement traces (vertical direction) when viewing condition changed from monocular (right eye viewing) to binocular.

Applying the Transformation to Other Patients' Data

Apart from the six patients with consistent PRLs included above, three other patients (for whom the consistency of the PRLs was not known) were included (P7 to P9). The absolute locations of the PRL relative to the middle of the optic disc measured with the microperimeter (monocular viewing) and determined with transformed data from the eye-tracker for monocular and binocular viewing are shown in Table 4.

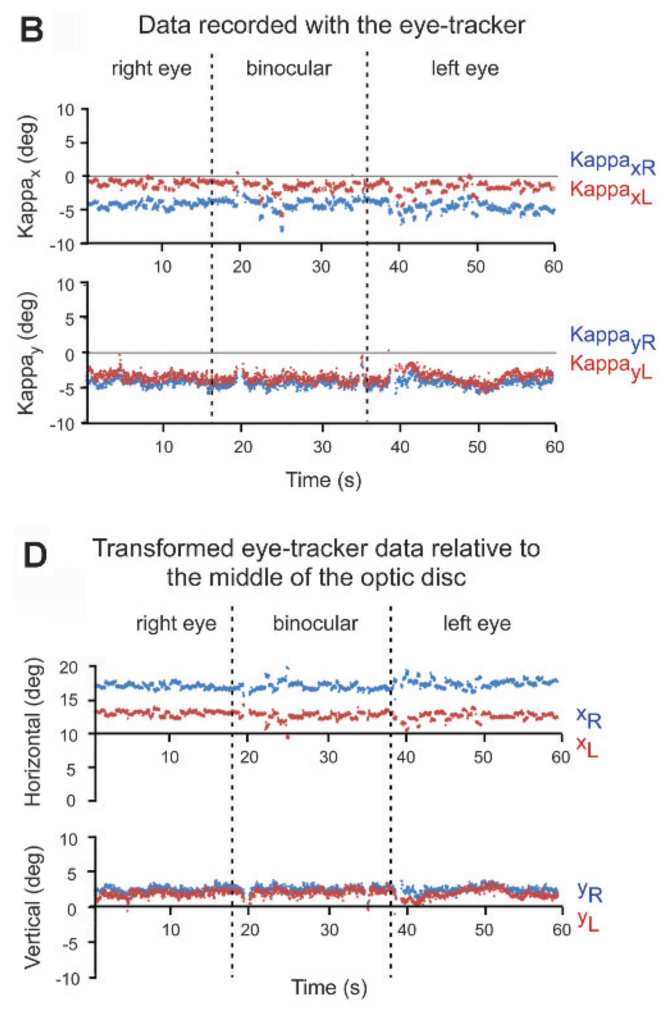
Table 4 shows that for P8 and P9, there was a good agreement between the locations of the PRL recorded with the microperimeter and calculated with the transformed data from the eye-tracker. Also, for these two patients, a shift in the PRL location was not evident when viewing condition changed from monocular to binocular. For P7, the monocular PRL locations recorded with the microperimeter and the eye-tracker (transformed data) were different. Also, there was a change in PRL location in the worse eye during binocular viewing, landing on the scotoma (Fig. 5). This change can also be observed in the eye movement traces as a horizontal shift when viewing condition changes from binocular to monocular with the left eye as the viewing eye.

DISCUSSION

Until now, technological limitations have prevented us from determining the absolute locations of the PRLs simultaneously for the two eyes. Instruments that allow the identification of the absolute location of the PRL are only monocular, whereas binocular eye-trackers provide only relative changes in the locations of the PRLs when viewing changes from monocular to binocular. In

A

	OD (deg)		OS (deg)	
	x	y	x	y
Monocular MP-1	16.3	0.8	12.8	1.5
Monocular eye-tracker	16.8	2.8	13.3	2.2
Binocular eye-tracker	16.7	3.2	12.7	2.7



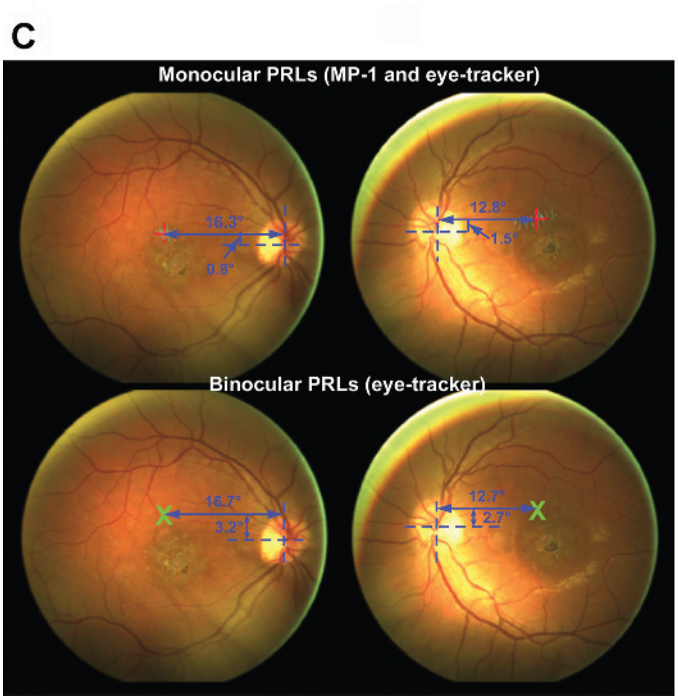


FIGURE 3.

The locations of the monocular and binocular PRLs did not change for P2. (A) Monocular PRLs relative to the optic disc measured with the microperimeter and calculated with the eye-tracker, one eye at a time, and binocular PRLs estimated from the eye-tracker recordings, simultaneously for the two eyes during binocular viewing. (B) Time course of fixation recorded with the eye-tracker in monocular and binocular viewing conditions. (C) Drawn on the fundus photographs, monocular PRLs recorded with the microperimeter and binocular PRLs estimated from the eye-tracker recordings (transformed data). (D) Time course of fixation with transformed eye-tracker data, showing PRL position relative to the middle of the optic disc.

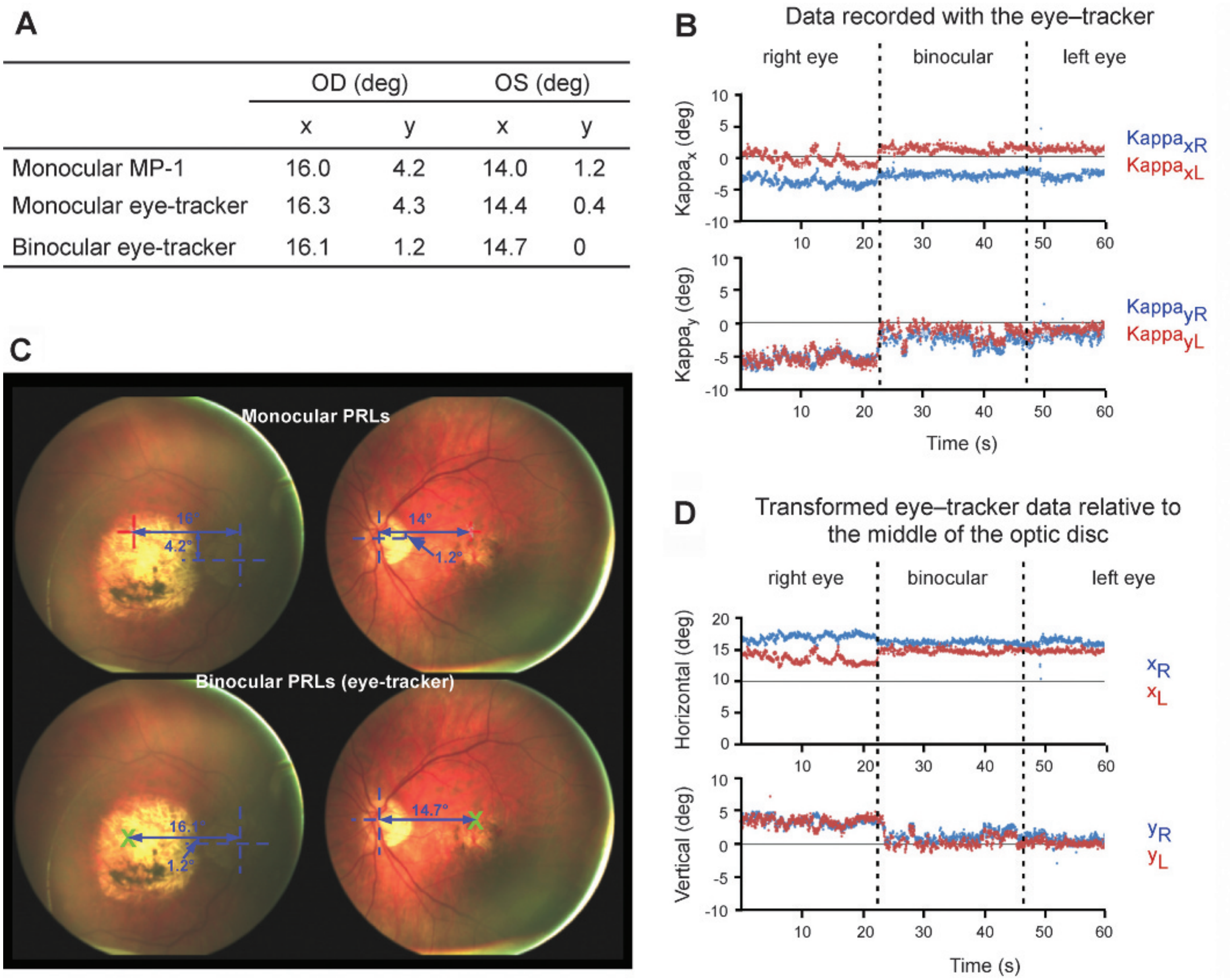


FIGURE 4.

Monocular PRL in the worse eye changes location during binocular viewing for P6. (A) Monocular PRLs relative to the optic disc measured with the microperimeter and calculated with the eye-tracker, one eye at a time, and binocular PRLs estimated from the eye-tracker recordings, simultaneously for the two eyes during binocular viewing. (B) Time course of fixation recorded with the eye-tracker in monocular and binocular viewing conditions. (C) Drawn on the fundus photographs, monocular PRLs recorded with the microperimeter and binocular PRLs estimated from the eye-tracker recordings (transformed data). (D) Time course of fixation with transformed eye-tracker data, showing PRL position relative to the middle of the optic disc.

the present study, we have shown that using the pupillary axes of the eyes allows us to identify the absolute locations of the PRLs simultaneously for the two eyes.

The eye-tracker used here estimates the pupillary axes of both eyes without a user calibration routine[8–10] and allows us to determine the horizontal and vertical components of the angle

TABLE 4.

Monocular PRL locations (relative to the middle of the optic disc) obtained with the microperimeter and the eye-tracker, and binocular PRL locations measured with the eye-tracker

	Monocular PRL location with microperimeter, degrees				Monocular PRL location with the eye-tracker, degrees				Binocular PRL location with the eye-tracker, degrees			
	OD		OS		OD		OS		OD		OS	
ID	x	y	x	y	x	y	x	y	x	y	x	y
P7	23.0	5.0	24.4	−3.5	23.5	0.5	23.0	−0.9	23.2	0.0	12.3	1.7
P8	17.0	−1.0	15.0	−2.5	17.9	−0.8	16.3	0.1	17.9	−0.7	16.4	0.0
P9*	21.5	6.5	N/A	N/A	20.9	6.6	9.3	11.0	20.6	6.5	9.4	8.3

*PRL location for the left eye could not be recorded with the microperimeter.
N/A, not available.

A

	OD (deg)		OS (deg)	
	x	y	x	y
Monocular MP-1	23.0	5.0	24.4	-3.5
Monocular eye-tracker	23.5	0.5	23.0	-0.9
Binocular eye-tracker	23.2	0	12.3	1.7

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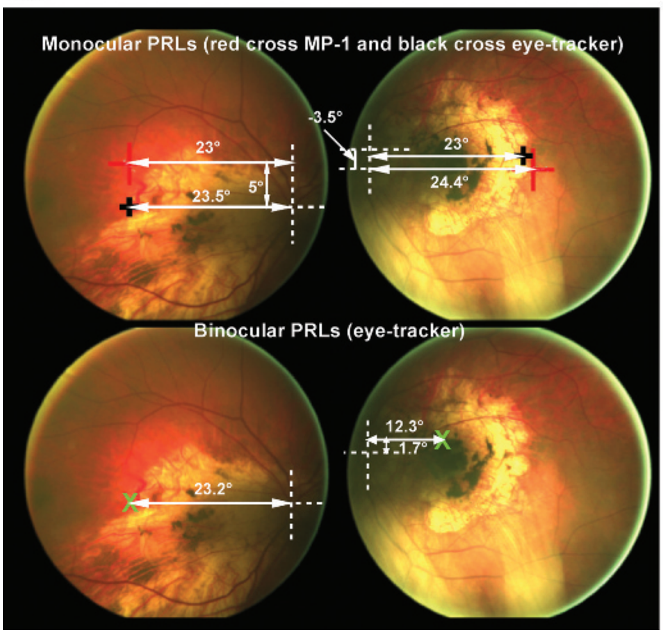

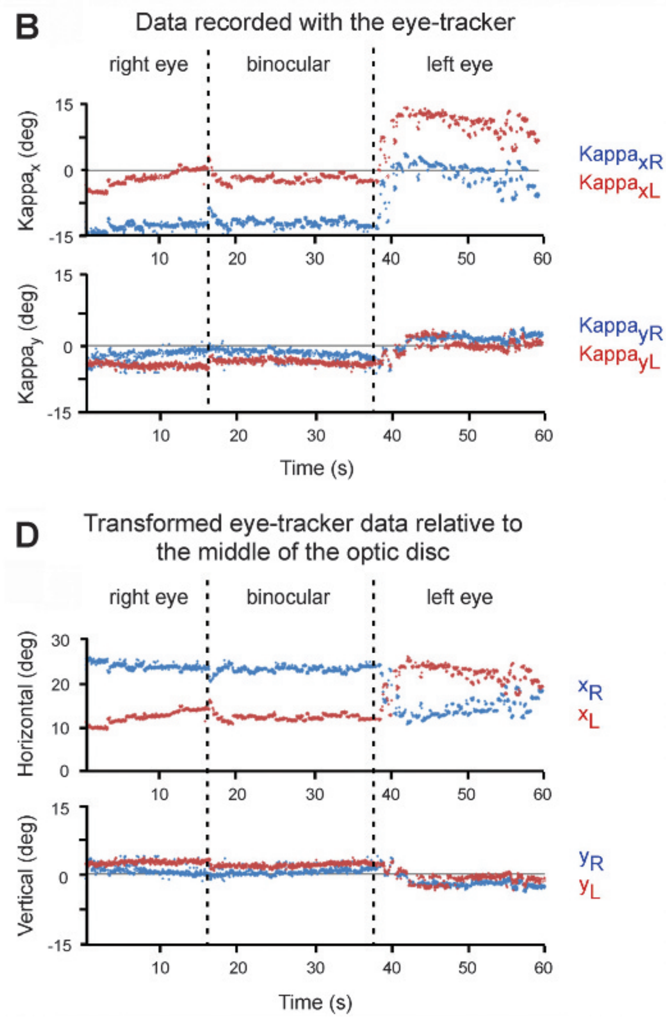

FIGURE 5.

For P7, Monocular PRL locations recorded with the two instruments were different, and PRL location in the worse eye changed during binocular viewing. (A) Monocular PRLs relative to the optic disc measured with the microperimeter and calculated with the eye-tracker and binocular PRLs estimated from the eye-tracker recordings simultaneously for the two eyes during binocular viewing. (B) Time course of fixation recorded with the eye-tracker in monocular and binocular viewing conditions. (C) Drawn on the fundus photographs, monocular PRLs recorded with the microperimeter and binocular PRLs estimated from the eye-tracker recordings (transformed data). (D) Time course of fixation with transformed eye-tracker data, showing PRL position relative to the middle of the optic disc.

between the visual and pupillary axes (angle Kappa), simultaneously for the two eyes. Using monocular measures of the fovea's location for people with normal vision, a transformation between the eye-tracker data and the microperimeter data was created. This transformation was applied to the monocular data of patients with a consistent PRL location and produced relatively small errors that allowed us to apply the transformation to the eye-tracker data recorded during binocular viewing. The predicted PRLs were then located on the fundus photographs and, for all patients, at least one of the PRLs fell on functional retina.

With the exception of one patient who complained of diplopia during testing, the PRLs in the two eyes during binocular viewing were more or less in corresponding locations, although this was not always the case for the monocular PRLs. This is illustrated in Fig. 4, which shows how, for a patient with large interocular acuity differences, the monocular PRL in the worse eye moves into a corresponding position with the PRL of the better eye during binocular viewing. Although the new location of the PRL in the worse eye falls on the scotoma, the location of the PRL of the better eye remains unchanged, which is probably the most advantageous situation given that the PRL of the better eye dominates during binocular viewing.

The transformation was also applied to the data from three other patients for whom the consistency of the PRL was not known. The monocular PRLs recorded with the microperimeter and determined with transformed data from the eye-tracker were in agreement for two of these patients. Also, their PRL did not shift when viewing condition changed from monocular to binocular. For P7, however, the monocular PRL in the right eye (the better eye) recorded with the eye-tracker was quite different from that recorded with the MP-1 but landed in functional retina (Fig. 5) in both circumstances. The change in monocular PRL location with the two devices, especially for the good eye, could have happened for two reasons: (1) the use of two monocular PRLs may be an adaptive mechanism to extensive central vision loss or (2) the right eye had only recently become the better eye.

The left eye had been the better eye, but the recovery after a successful cataract surgery coincided with a decline in vision in this eye, to the point that it has become the worse eye since then.

The information about the locations of the PRLs simultaneously in the two eyes has been long sought after by researchers working in the field of low vision because the impairments in binocular vision of patients with central vision loss are not well understood. Also, this information may be helpful in deciding the best course of action for the rehabilitation process for each patient.[14,15] For example, in the case of the patient with very low vision (P7), the monocular PRL of the left eye and that of the right eye are on opposite sides of each eye's large central scotoma and therefore in noncorresponding positions. During binocular viewing, however, the PRL of the slightly worse eye moves to a corresponding position with the PRL of the better eye while falling on the scotoma. Consequently, during binocular viewing, the patient is left with the visual input from only one eye. This patient would probably benefit from PRL relocation training to the upper part of the retina of the two eyes, provided that the trained location is within the same distance from the former fovea as the original PRL[16] to maintain the same level of resolution. This position is beneficial for reading not only because it provides a larger visual span but also because the two PRLs will fall on functional retina.

Limitations

This is a proof-of-principle study and some limitations must be acknowledged. The eye-tracker measures eye movements based on anatomical assumptions described elsewhere[10] and individual factors, such as corneal shape and the roundness of the pupil, affect the accuracy of the measurements. In addition, we have not tested this eye-tracker on patients with central vision loss and high myopia or hypermetropia. For these patients, the eyeball is elongated/shortened and the offset between the eye-tracker and the microperimeter would probably be different from that reported in this article. Although slightly lower/higher angle Kappa has been reported in myopic/hyperopic eyes than in emmetropic eyes,[17] a strong relationship between refractive error and angle Kappa has not always been found.[18]

There are conflicting reports about the relationship between angle Kappa and age. For example, Hashemi et al.[19] report a slow decrease of angle Kappa of 0.015 degrees/y, whereas Berrio et al.[20] did not find a significant relationship between angle Kappa and age. A decrease of 0.015 degrees/y in angle Kappa implies a decrease of only 0.5 degrees in our clinical sample compared with control subjects [$(79 - 44) \times 0.015 = 0.5$ degrees]. Moreover, the mean angle Kappa for control subjects that we found here (1.5 degrees) is in close agreement with Loper's[21] (1.4 degrees) using the corneal reflex in relation to the center of the cornea.

Another source of error would be the variability in the location of the fovea relative to the middle of the optic disc. The average values we used here are in strong agreement with published results.[11,13] The variability of the location of the fovea only affects the calculation of the coordinates of the point where the pupillary axis intersects the retina, relative to the middle of the optic disc. These coordinates were obtained from normal control subjects. Based on the coordinates of this point (from control subjects) and the horizontal and vertical components of angle Kappa (for the patients), we were able to infer the location of the PRL relative to the middle of the optic disc in monocular and binocular viewing conditions. Although we acknowledge that these locations are not free of errors, we report quite good agreement between monocular PRL measured with the microperimeter and those calculated from the eye-tracker's data. We did not report any measurements relative to the fovea for the patients, nor did we infer its location for them.

In conclusion, this study showed that, by transforming the measurements of the PRL location obtained with the eye-tracker into measurements relative to the middle of the optic disc, the absolute location of the PRLs during binocular viewing can be predicted with acceptable accuracy. Once this transformation is obtained, there is no need for an imaging instrument to determine the absolute location of the PRLs.

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