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Head and Gaze Behavior in Retinitis Pigmentosa

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Purpose. Peripheral visual field loss (PVFL) due to retinitis pigmentosa (RP) decreases saccades to areas of visual defect, leading to a habitually confined range of eye movement. We investigated the relative contributions of head and eye movement in RP patients and normal-sighted controls to determine whether this reduced eye movement is offset by increased head movement.

Methods. Eye-head coordination was examined in 18 early-moderate RP patients, 4 late-stage RP patients, and 19 normal-sighted controls. Three metrics were extracted: the extent of eye, head, and total gaze (eye+head) movement while viewing a naturalistic scene; head gain, the ratio of head movement to total gaze movement during smooth pursuit; and the customary oculomotor range (COMR), the orbital range within which the eye is preferentially maintained during a pro-saccade task.

Results. The late-stage RP group had minimal gaze movement and could not discern the naturalistic scene. Variance in head position in early-moderate RP was significantly greater than in controls, whereas variance in total gaze was similar. Head gain was greater in early-moderate RP than in controls, whereas COMR was smaller. Across groups, visual field extent was negatively correlated with head gain and positively correlated with COMR. Accounting for age effects, these results demonstrate increased head movement at the expense of eye movement in participants with PVFL.

Conclusions. RP is associated with an increased propensity for head movement during gaze shifts, and the magnitude of this effect is dependent on the severity of visual field loss.

Keywords: retinitis pigmentosa, eye movement, head movement, eye-head coordination

Visual scanning using a coordinated combination of head and eye movement is critical to human vision. For individuals with peripheral visual field loss (PVFL) due to retinitis pigmentosa (RP), exploring a visual scene necessarily requires a greater degree of scanning. The eye-head coordination of RP patients during visual scanning is of interest to clinicians and orientation and mobility specialists who could train patients to scan their surroundings more effectively.

Studies on the effect of PVFL on eye and head movement have yielded conflicting results. The hypothesis that PVFL may disrupt the generation of reactive saccades to visually salient targets (bottom-up saccade control) is supported by the finding that patients with simulated and actual PVFL make fewer than expected saccades into areas of visual defect in a visual search task[1,2] and have a more confined range of eye movement during locomotion.[3] Contrarily, in a different study, PVFL patients made beyond-visual-field saccades frequently during locomotion, and there was no difference in eye movement behavior between PVFL patients and normal-sighted controls.[4] Furthermore, the degree of gaze (eye+head) movement was found to be greater in PVFL patients compared with controls in an indoor walking task[5] but smaller in a traffic gap judgment task.[6] In the only PVFL study to our knowledge that has considered the relative contributions of eye and head movement, participants with RP used increased horizontal head movement and a similar eye movement during locomotion compared with healthy sighted controls.[7] None of the aforementioned studies have considered age or field of view extent as possible correlates for eye and head behavior in RP. It is known that healthy subjects can adapt to artificial restrictions of the field of view or oculomotor range by increasing the relative contribution of head movement to overall gaze movement, but it remains unclear whether this effect is observed in RP.[8–11]

In the present study, we investigated the relative contributions of head and eye movement in RP patients and normal-sighted controls during three head-unrestrained tasks. Three measures of head movement propensity were extracted: the extent of eye, head, and gaze (eye+head) movement while viewing a naturalistic scene; head gain (the ratio of head movement to total gaze movement) during a smooth pursuit task[12]; and the customary oculomotor range (COMR), which measures the orbital range within which the eye is preferentially maintained during a saccade task.[13] We hypothesized that PVFL due to RP would lead to greater reliance on head movement and therefore visual field extent would be negatively correlated with propensity for head movement.

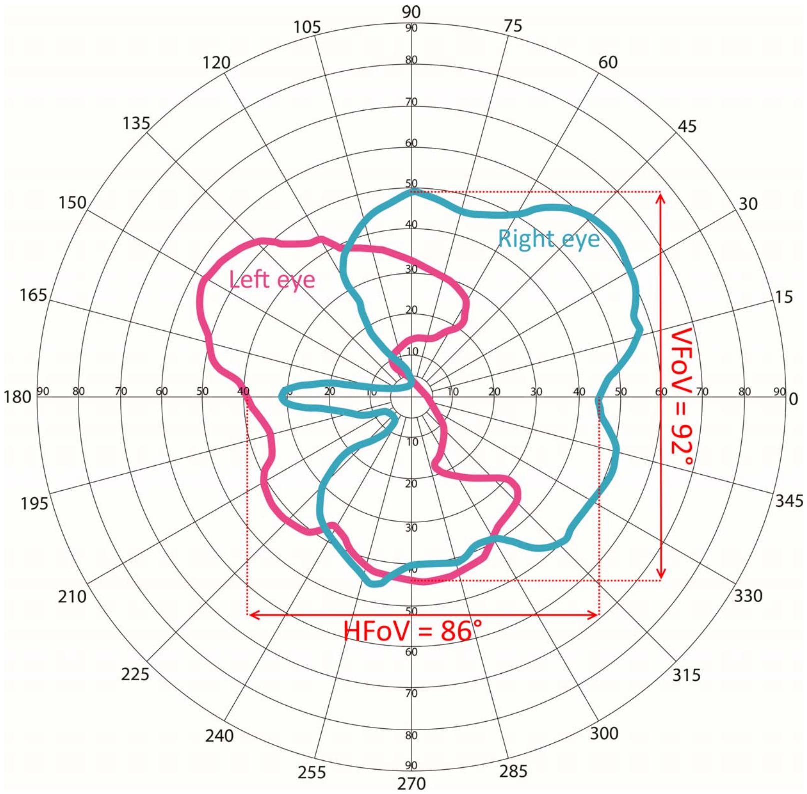

Figure 1. Example of Goldmann perimetry for an RP patient. The visual fields of the left eye (*magenta*) and right eye (*blue*) are overlaid on the same chart using the methodology of Turano et al.[14] and the binocular HFoV and VFoV (*red arrows*) are taken as the width along the horizontal and vertical meridians of the binocular visual field. Peripheral islands were not included in the calculated field of view.

Methods

Participants

Eighteen early- to moderate-stage RP patients (early-moderate RP group, aged 31–84), four late-stage RP patients (late RP group, aged 55–82), and 19 normal-sighted participants (control group, aged 30–82), took part in the study. The RP patients were categorized as early-moderate RP or late RP based on their ability to perform a central fixation task for eye-tracker calibration. Participants in the control group all had best-corrected visual acuity (BCVA) better than 6/12 in both eyes. Ten patients in the early-moderate RP group used no mobility aid regularly, six used a long cane, one used an identification cane, and one used both a long cane and a guide dog. All participants in the late RP group used a long cane regularly and one used both a long cane and a guide dog. None of the participants in any group exhibited nystagmus, amblyopia, or strabismus. The study was approved by the Royal Victorian Eye and Ear Hospital Human Research and Ethics Committee, and was carried out in accordance with the tenets of the Declaration of Helsinki with the informed consent of all participants.

The residual visual field of each RP patient was measured with the Goldmann manual kinetic perimetry test by an experienced examiner using a size 5 target, chosen so as to be similar in size to the task stimuli. We defined the horizontal and vertical field of view (HFoV, VFoV) as the width of the binocular visual field along the horizontal and vertical meridian lines, respectively, when the fields of view of both eyes were overlaid with the retinal fixation points aligned (Fig. 1), as described in Turano et al.[14] Confrontation testing and optometric examination performed by an experienced clinician confirmed that the control group was without significant visual field loss or retinal or optic nerve disease.

Eye and Head Tracking

A head-mounted infrared eye tracker (Arrington Research, Scottsdale, AZ, USA) was used to track the eye-in-head angle of both eyes at 60 Hz. The system was calibrated by presenting a series of targets at predefined locations spanning approximately 80 × 50°, on which the participant was required to fixate while keeping his or her head stationary in a chin rest. The chin rest was removed after the calibration was complete. Four RP patients were unable to complete the fixation task independently due to poor central fixation. In these cases, it was necessary for the researcher to verbalize the target location (e.g., "top right") and to tap on the target to provide a directional audio cue for localization. These patients were allocated to the late RP group on account of their poor central fixation. Goldmann perimetry data for these participants included at most only a single detection at the origin, corresponding to a horizontal and vertical field of view smaller than 1°. An electromagnetic tracking tag (Ascension Technology Corporation, Shelburne, VT, USA) fastened to the eye-tracker headset worn by the participant recorded the head position and orientation at 20 Hz. Head tracker data were up-sampled to 60 Hz using a linear interpolator to match the sample rate of the eye tracker.

Experiment Procedure

Participants wore the eye- and head-tracking apparatus and were seated 1 m in front of a large projector screen that spanned 88 × 57° of visual arc, and were free to move their

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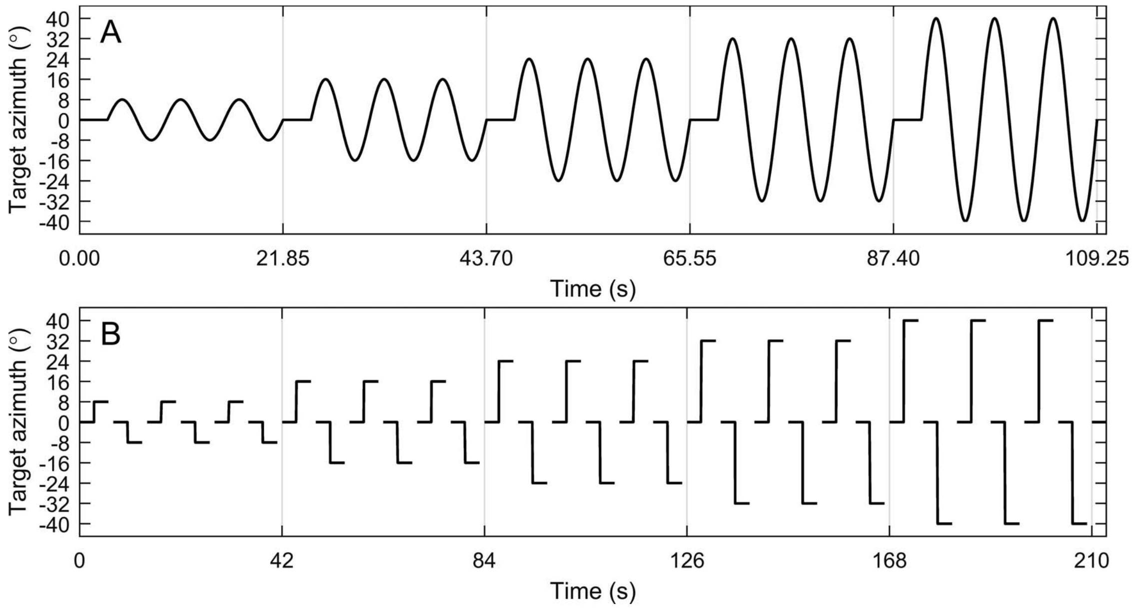

Figure 2. Target position during a single execution of the horizontal smooth pursuit task (**A**) and horizontal saccade task (**B**). *Vertical gray lines* delimit triplets of equal-amplitude oscillations. The targets followed an obvious pattern so as to accommodate participants with PVFL.

heads for the duration of the experiment except during eye-tracker calibration. Five participants in the control group and one participant in the early-moderate RP group wore corrective spectacle lenses during the experiment. Stimuli were presented on the screen in a naturalistic scene task, a smooth pursuit task, and a saccade task, each described below. The smooth pursuit and saccade tasks occurred in both horizontal and vertical configurations. All participants performed the naturalistic scene task first, and then performed the saccade and smooth pursuit tasks in each configuration once. This was then repeated so that each task and configuration were performed twice in total. The configuration of each smooth pursuit task was prescribed by a balanced-random schedule, and each smooth pursuit task was followed by a saccade task in the same configuration. The late RP group completed two repetitions of the naturalistic scene task but could not perform the smooth pursuit and saccade tasks.

Naturalistic Scene Task

The participant was required to passively watch a short computer-generated film that featured streams of moving traffic crossing a busy intersection in a single continuous shot from an elevated angle (*Rush Hour*, Fernando Livschitz).[15] The film was 63 seconds in duration and was preceded by a 4° circular white fixation target that was presented in the center of the display for 10 seconds. From the observer's perspective, traffic moved along both the horizontal and vertical medians, covering most of the lower two-thirds of the projected image.

Smooth Pursuit Task

The participant was required to track a 4° circular white target with his or her gaze as it moved smoothly along a 1-dimensional horizontal or vertical path. The target began in the center of the display and remained stationary for 3 seconds before describing three full sinusoidal oscillations of equal amplitude along the path, and then stopped in the central position again. After pausing in the central position for 3 seconds, the target completed another set of three oscillations with greater amplitude than the first set. This was repeated until five sets had been completed with incrementally increasing amplitudes. In the horizontal configuration of the task, the five sets had amplitudes of ±8°, 16°, 24°, 32°, and 40°, whereas in the vertical configuration the five sets had amplitudes of ±5°, 10°, 15°, 20°, and 25° (limited by the aspect ratio of the projected display). Figure 2A plots the target position for a full execution of the horizontal configuration of the task. The period of oscillation was constant regardless of amplitude, such that the peak velocity (velocity at zero-crossing) increased with oscillation amplitude up to a maximum of 40°/s (Table 1).

Saccade Task

The participant was required to fixate on 4° circular white targets as they appeared in predefined locations on a 1-dimensional horizontal or vertical path. In each trial, a fixation target was presented in the central position for 3 seconds. Then the central target was extinguished and an eccentric target appeared simultaneously. After a presentation period of 3 seconds, the eccentric target was extinguished, at which time the subject was required to return his or her gaze to the remembered location of the central target. This was accompanied by an audio cue to prompt participants who had not successfully located the eccentric target to return their gaze to the center. One second after the offset of the eccentric target, the central target was re-presented, marking the beginning of the next trial. The eccentric targets appeared in sets of six, with constant amplitude and alternating polarity within a set. The task finished when five sets (30 eccentric targets total) had been presented. As in the smooth pursuit task, the target amplitude increased incrementally with each set. In the horizontal version of the task, the five sets had amplitudes of ±8°, 16°, 24°, 32°, and 40°, whereas in the vertical version the five sets had amplitudes of ±5°, 10°, 15°, 20°, and 25°. Figure 2B plots the target position for a full execution of the horizontal configuration of the task. The target locations followed an easily predictable to-and-fro pattern in a single plane so as to accommodate participants with PVFL.

Table 1. Amplitude, Period, and Peak Velocity of the Oscillating Smooth Pursuit Target

Path Orientation	Amplitude, deg	Period, s	Velocity at Zero-crossing, deg/s
Horizontal	8	6.28	8
	16	6.28	16
	24	6.28	24
	32	6.28	32
	40	6.28	40
Vertical	5	7.18	8
	10	7.18	16
	15	7.18	24
	20	7.18	32
	25	7.18	40

Data Analysis

Eye and Head Tracking. Eye-in-head (orbital) azimuth and elevation (°) were measured using the eye tracker, and head-in-space position (mm), azimuth angle (°), and elevation angle (°) were measured using the motion tracker. Eye-tracker data were processed to remove blink artifact, then for each trial one eye was nominated for further analysis based on a quality statistic reported by the eye-tracker system. Motion tracker measurements were found to be free of artifact without any processing. For the smooth pursuit and saccade tasks, only head and eye movements in the direction congruent with target movement were analyzed.

Naturalistic Scene Task. Eye and head position measurements were summated to produce the gaze position at all time points during the task. The dispersion of gaze locations during the task was quantified by the area of the bivariate contour ellipse encompassing 68% of the gaze locations measured over the duration of the task (Fig. 3).[16] Gaze dispersion was calculated separately for each repetition of the task and then averaged to produce a single measure for each participant. Eye position dispersion and head position dispersion were similarly defined for the eye and head components of gaze separately, allowing for an assessment of the relative contributions of the eye and head movement to overall gaze movement.

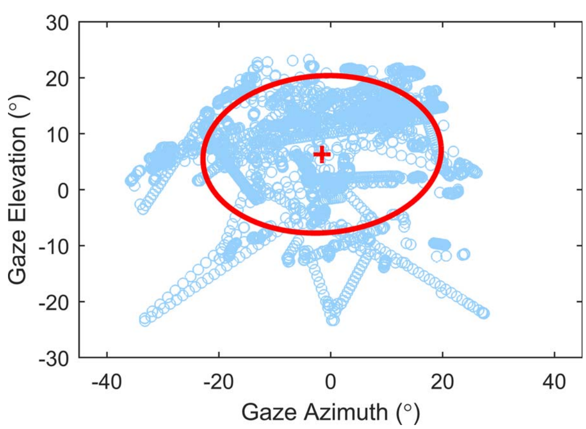

Figure 3. Gaze location of a control subject during the naturalistic scene task. Eye and head position measurements were summated to produce the gaze point relative to the center of the projector screen at all time points (*light blue dots*). The dispersion of gaze positions is quantified by the area of the bivariate contour ellipse (*red*) that encompasses 68% of the gaze position measurements over the trial. Eye and head position dispersion were similarly defined for the eye and head components of gaze separately. The display spanned approximately 88° × 57° of visual arc.

Smooth Pursuit Head Gain. The contribution of head movement to smooth pursuit was quantified by the head gain, as described by Proudlock et al.[12] Horizontal head gain (HHG) was calculated from the horizontal component of gaze during the horizontal variant of the task, and vertical head gain (VHG) was calculated from the vertical component of gaze during the vertical variant of the task. For each full oscillation of the smooth pursuit target, we found the difference between the two most extreme excursions of the head (Δ*head*) and eye (Δ*eye*), as shown in Figure 4. The head gain for the trial was then given by $HeadGain_{trial} = \frac{\Delta head}{\Delta eye + \Delta head}$ and could range from 0 (no head movement, entirely eye movement) to 1 (no eye movement, entirely head movement). The mean head gain over the entire stimulus set was used as a measure of head movement propensity and is referred to simply as "head gain" from this point onward.

Saccade Task COMR. Each presentation of an eccentric saccade target constituted a single trial, and resulted in a single gaze shift. These gaze shifts were used to calculate the COMR of each subject, as described by Stahl.[13] Retrograde saccades to central targets at the conclusion of each trial were not included in the analysis. Horizontal COMR (HCOMR) was calculated from the horizontal component of gaze during the horizontal variant of the saccade task, and vertical COMR (VCOMR) was calculated from the vertical component of gaze during the vertical variant of the task.

A gaze shift was defined as the summation of an eye movement ($\Delta eye = eye_{final} - eye_{initial}$) and a head movement ($\Delta head = head_{final} - head_{initial}$) as shown in Figure 5. Eye saccades were defined as any period of eye movement with velocity exceeding 30°/s, and head saccades were defined as any period of head movement with velocity exceeding 5°/s. The first eye saccade made within 800 ms of target onset was nominated as the response eye saccade for each trial. The eye saccade end point was extended to capture any subsequent corrective eye saccades that were initiated up to 130 ms after the offset of the initial eye saccade. Then, if a head saccade was

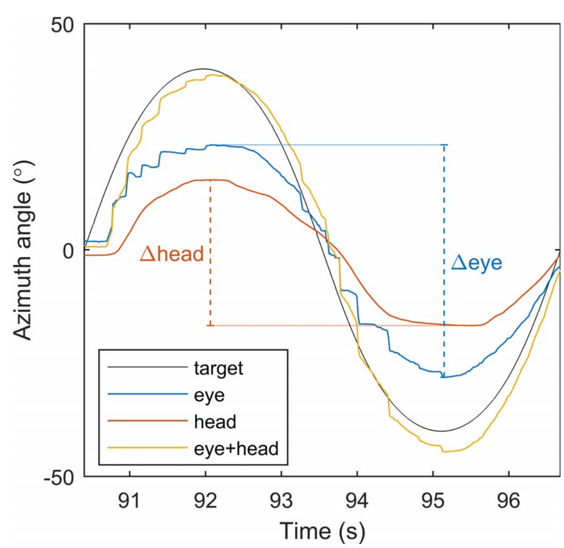

Figure 4. Eye and head movement during a single oscillation of the smooth pursuit target (±40° eccentricity). ΔH and ΔE were measured between the leftmost and rightmost excursions of the head and eye and were used to calculate the head gain for the trial, equal to Δ*head*/(Δ*eye*+Δ*head*) as per Proudlock et al.[12] Head gain could range from 0 (no head movement, entirely eye movement) to 1 (no eye movement, entirely head movement).

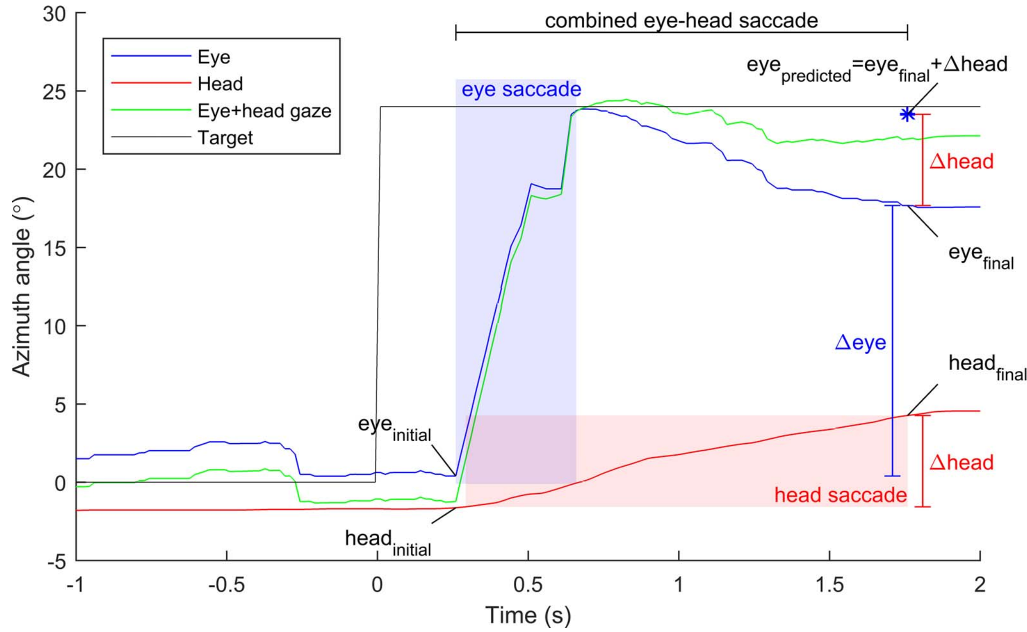

FIGURE 5. Eye and head azimuth during a combined eye-head saccade to an eccentric target during the horizontal saccade task. An eye saccade (*blue shaded region*) and a slower head saccade (*red shaded region*) together comprise an eye-head saccade (*black bar*). The eye saccade includes an initial large saccade followed a short time later by a smaller corrective saccade.

initiated up to 100 ms before or 50 ms after the response eye saccade, the gaze shift was classified as a combined eye-head saccade, and the start and end points of the gaze shift were chosen to fully enclose both the eye and head saccades. If no head saccade occurred, then the gaze shift was classified as eye-only, and the start and end points were equal to the eye saccade onset and offset. If no eye saccade occurred, or if the initial eye saccade was in the wrong direction, then the trial was discarded. The accuracy of a gaze shift (the proximity of the final gaze point to the target) was unimportant, as the fixation targets simply acted as prompts to elicit saccadic gaze movement over a range of eccentricities.

The predicted orbital eccentricity, $eye_{predicted}$, is defined in Stahl[13] as the eccentricity that would have occurred if a gaze shift of the same amplitude had been executed with no contribution from head movement; that is,

$$eye_{predicted} = eye_{final} + \Delta head = eye_{initial} + \Delta eye + \Delta head$$

An accurate saccade to an eccentric target $eye_{predicted}$ is therefore approximately equal to the target location relative to the initial head position. Stahl's[13] method is predicated on the theory that head movement acts to confine actual orbital eccentricity at the conclusion of the gaze shift (eye_{final}) to some comfortable central range, the COMR, and therefore head movements only occur during gaze shifts that would otherwise result in the eye falling beyond that range ($eye_{predicted}$ outside of COMR). This gives rise to the characteristic plot of $\Delta head$ against $eye_{predicted}$ (Fig. 6A) featuring a flat central region of almost no head movement in which $eye_{predicted}$ is approximately equal to eye_{final}, flanked by two sloping lobes in which head movements act to confine eye_{final} to the COMR. Note that it is possible for $eye_{predicted}$ to exceed the maximum target amplitude of $\pm 40°$ depending on the initial eye and head position.

The COMR was calculated from $F(eye_{final})$, the distribution of frequency of occurrence of eye_{final} (Fig. 6B), and $F(eye_{predicted})$, the distribution of frequency of occurrence of $eye_{predicted}$, (Fig. 6C), both approximated using kernel density estimation. $F(eye_{final})$ was then divided pointwise by $F(eye_{predicted})$ to normalize against the effect of the task-specific distribution of targets, resulting in $F(eye_{final})^*$. The COMR was then defined as the range of orbital eccentricities encompassing the central 90% of the area beneath $F(eye_{final})^*$ (Fig. 6D). In theory, head movements are used to ensure that eye position falls within the COMR at the conclusion of a gaze shift 90% of the time.

Statistical Analyses

Participants were divided into three groups for statistical analysis: control ($n = 19$), early-moderate RP ($n = 18$), and late RP ($n = 4$). Gaze, eye, and head position dispersion during the naturalistic scene task were compared among the three groups using 1-way ANOVAs with Tukey's test for multiple comparisons. Visual inspection of the residual normal Q-Q plots confirmed that the residuals were approximately normally distributed for each test with the exception of the test on head position dispersion. The analysis on head position dispersion was therefore repeated using a nonparametric Kruskal-Wallis ANOVA on ranks with Dunn's test for multiple comparisons.

Head gain and COMR were then compared between the early-moderate RP group and the control group. We tested the effect of group (early-moderate RP or control) on head movement propensity using a generalized linear model (gamma distribution, log link function) on COMR and head gain with group as a factor and age as a continuous predictor. We then tested the correlation between field of view and head movement propensity using a generalized linear model (gamma distribution, log link function) on COMR and head gain with age and field of view as continuous predictors. Note that as group and field of view were highly correlated, they could not both be included as predictors in the same model. Vertical and horizontal data were analyzed separately. For the control group, a normal healthy field of view of $200 \times 135°$ was inferred from their lack of retinal or optic nerve disease.[17] All statistical analyses were performed with Minitab18 statistics software (Minitab Inc., State College, PA, USA).

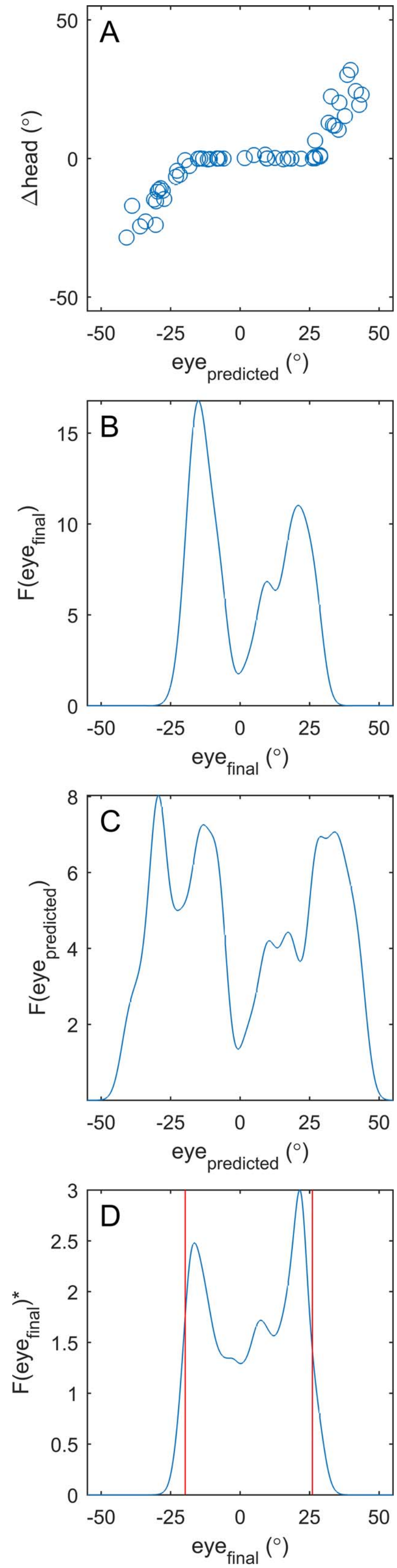

Figure 6. Derivation of COMR using the methodology of Stahl.[13] (**A**) Head movement against $eye_{predicted}$, the eye eccentricity that would have occurred if a gaze shift of the same amplitude had been executed with no contribution from head movement. This plot characteristically features a central flat region in which head movements do not occur and two flanking sloped regions in which head movements are used to confine the orbital eccentricity to some central range. (**B**) Frequency of occurrence of eye_{final}, the final eye eccentricity at the conclusion of the gaze shift. (**C**) Frequency of occurrence of $eye_{predicted}$. (**D**) Normalized frequency of occurrence of eye_{final}, calculated by pointwise division of $F(eye_{final})$ by $F(eye_{predicted})$ to eliminate the effect of the task-specific distribution of targets. The COMR (*red lines*) is the range enclosing 90% of the area under the curve.

Results

Participants in the early-moderate RP and control groups were able to complete all tasks. The four participants in the late RP group performed only the naturalistic scene task. None of these participants were able to accurately describe any content of the scene. Means, SDs, and ranges for visual assessment results and head movement propensity measures are presented in Table 2. The mean (±SD) BCVA was 0.36 ± 0.29 logMAR for early-moderate RP and 1.00 ± 0.60 logMAR for late RP, and the mean visual field extent was 29 ± 31° by 28 ± 29° for early-moderate RP and 0.25 ± 0.43° by 0.25 ± 0.43° for late RP.

Gaze While Viewing a Naturalistic Scene

None of the late RP group was able to accurately describe any details of the scene in the naturalistic scene task. An example of gaze position during the task and the calculation of gaze dispersion is given in Figure 3. Eye, head, and gaze dispersion during the task are plotted for each group in Figure 7. Comparing the late RP group with the control group and early-moderate RP group, gaze and eye position dispersion were significantly smaller in the late RP group ($P < 0.001$), whereas head position dispersion was not significantly different ($P =$ 1.000 versus control; $P = 0.286$ versus early-moderate RP). Head position dispersion in the early-moderate RP group was significantly greater than in the control group ($P = 0.022$) but there was no significant difference in gaze or eye position dispersion between the early-moderate RP and control groups (eye: $P = 0.148$; gaze: $P = 1.000$).

Factors Affecting Head Movement Propensity

A positive correlation was found between HHG and VHG (Pearson's $R^2 = 0.65$, $P < 0.001$) and between HCOMR and VCOMR ($R^2 = 0.69$, $P < 0.001$). Head gain was negatively correlated with COMR in the horizontal direction ($R^2 = 0.63$, $P < 0.001$) and in the vertical direction ($R^2 = 0.65$, $P < 0.001$), demonstrating consistency between the two measures of head movement propensity. HHG and VHG and COMR (HCOMR, VCOMR) are plotted against field of view and age in Figure 8. The results of a generalized linear model on head gain and COMR with group and age predictors are presented in Table 3, whereas the results of a generalized linear model on head gain and COMR with field of view and age as predictors are presented in Table 4. Age, group, and field of view extent each had a significant effect on HHG and VHG and COMR; however, a large degree of variation among individuals is evident (Fig. 8). There was no significant difference in variance in head gain or COMR between the two groups (Bonett's test, $P > 0.05$).

Minimal Head Movement in Some Participants

Some participants completed the saccade task with very little head movement even for the most eccentric targets, possibly because the saccade targets were not eccentric enough to evoke head movements in the individual. These subjects are denoted by crosses in Figure 8. This behavior produces a flat $\Delta head$ versus $eye_{predicted}$ plot (Fig. 9A) without the characteristic flanking sloped regions present in Figure 6, as well as an

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Table 2. Descriptive Statistics of Visual Assessment Results and Task Outcomes

	Early-Moderate RP, n = 18				Control, n = 19				Late RP, n = 4			
Measure	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**
Age	31	84	59	17	30	82	59	16	55	82	70	11
HFoV, deg	0	128	29	31	200	200	200	0	0	1	0.25	0.43
VFoV, deg	0	111	28	29	135	135	135	0	0	1	0.25	0.43
BCVA, logMAR	0.00	1.00	0.36	0.29	−0.30	0.20	−0.06	0.12	0.40	2.00	1.00	0.60
Gaze disp.	521.9	1743.3	943.3	301.5	473.1	1233.4	949.6	213.1	49.0	361.4	201.5	114.8
Eye pos. disp.	295.8	1268.7	640.8	249.1	427.1	1104.6	786.5	217.1	45.1	237.0	134.2	69.8
Head pos. disp.	4.8	306.2	114.5	101.9	2.5	147.5	36.8	44.1	0.3	166.2	52.5	66.6
HHG	0.02	0.65	0.25	0.23	0.01	0.66	0.12	0.16	-	-	-	-
VHG	0.02	0.60	0.19	0.18	0.01	0.67	0.10	0.16	-	-	-	-
HCOMR, deg	17.8	81.8	57.1	18.2	27.3	95.1	72.7	21.3	-	-	-	-
VCOMR, deg	12.1	75.7	48.5	19.0	23.8	80.0	61.8	15.8	-	-	-	-

Head gain and COMR values are not given for the late RP group as they did not perform the smooth pursuit and saccade tasks. For the control group, a normal healthy field of view of 200 × 135° was inferred from their lack of retinal or optic nerve disease.[17] disp., dispersion; max, maximum; min, minimum; pos., position.

abruptly truncated $F(eye_{final})^*$ (Fig. 9D). This behavior was observed in four early-moderate RP patients (22%) and nine control subjects (47%) in both the vertical and horizontal directions.

Discussion

PVFL Associated With Increased Head Movement Propensity

In the naturalistic scene task, the late RP group had significantly smaller gaze dispersion than both the early-moderate RP group and the control group, which was primarily driven by a relative lack of eye movement. Considering that none of the late RP group was able to describe any features of the scene, it is likely that this behavior was caused by a lack of salient visual stimuli. Gaze dispersion was similar between the early-moderate RP and control groups, but in the early-moderate RP group, the head position dispersion was greater, supporting the theory that the contribution of head movement is increased in RP.

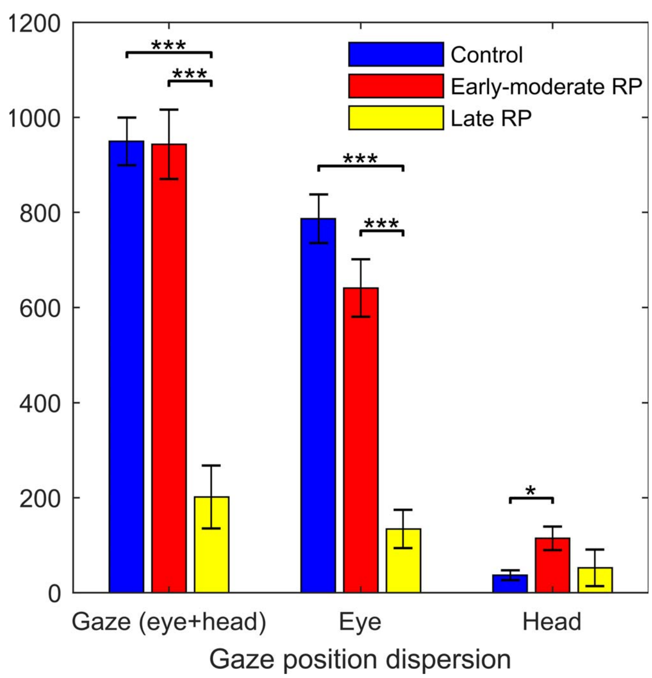

Figure 7. Comparison of mean (±SEM) gaze, eye, and head position dispersion between the control group, early-moderate RP group, and late RP group. *Asterisks* indicate significant differences (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$).

Mean horizontal COMR in the control group (aged 30–82) was 72.7 ± 21.3°, comparable to the value of 64.4 ± 16.4° reported by Thumser et al.[18] for a group of 60 healthy sighted participants aged 22 to 80. Mean HHG in the control group was 0.12 ± 0.16, comparable to the value of approximately 0.2 ± 0.2 (values read from figure) reported by Proudlock et al.[12] for a similar smooth pursuit task in 53 healthy sighted participants aged 20 to 83. The early-moderate RP group had significantly greater propensity for head movement than the control group during smooth pursuit and saccade tasks. Restricted field of view due to early-moderate RP was correlated with increased propensity for head movement in the tasks. These results support the hypothesis that PVFL is associated with a diminished range of eye movement and greater reliance on head movement. This may be driven by a habitually confined eye movement due to lack of peripheral stimulation.[4] Alternatively, it has been suggested that in PVFL, head/body orientation may be more reliable than eye orientation as a cue for spatial constancy, leading patients to favor head movement more heavily,[3] although this is contradicted by the finding that exploratory saccade training improved the performance of RP patients in a mobility task.[19]

The existing literature is divided on the relationship between PVFL and eye movement. Patients with PVFL have previously been shown to make few saccades into areas of visual defect during visual search[1]; make frequent saccades into areas of visual defect during visual search and locomotion[4]; make saccades of similar amplitude compared with healthy controls during locomotion[4]; make saccades of smaller amplitude compared with healthy controls during visual search (simulated PVFL)[2]; have more confined eye position than healthy controls in locomotion[3]; have a greater fixation area than healthy controls in locomotion[5]; and have a smaller fixation area than healthy controls in a traffic gap judgment task.[6] The wide variety of different tasks used makes it difficult to draw direct comparisons between different studies, particularly given the variable nature of tasks such as outdoor locomotion[4] and traffic gap judgment.[6] In addition, some of

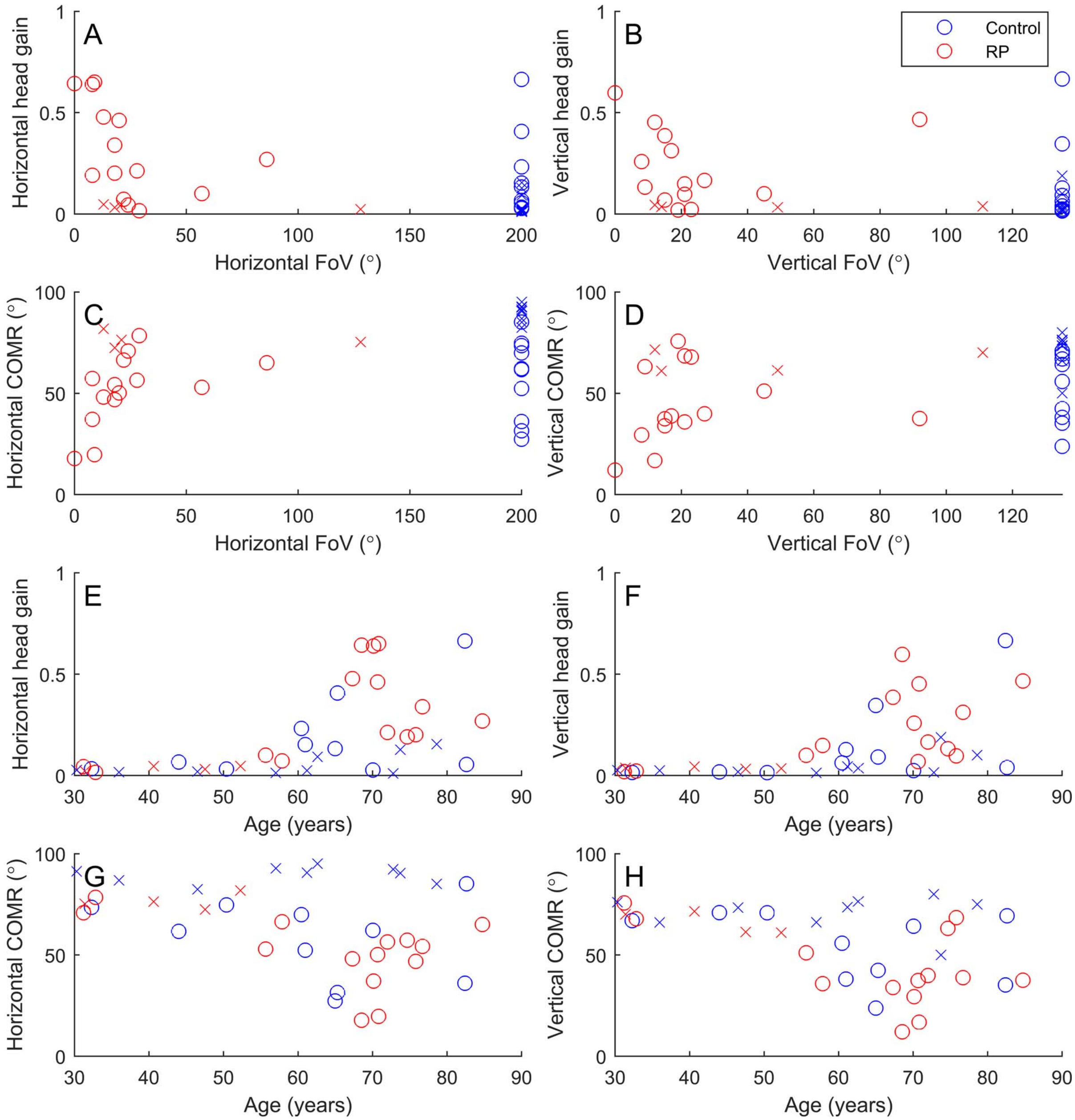

FIGURE 8. Factors affecting head movement propensity. HHG and VHG and COMR are plotted against age and field of view, with the early-moderate RP group in *red* and the control group in *blue*. For the control group, a normal healthy field of view of 200 × 135° was inferred from their lack of retinal disease.[17] Participants that were affected by a ceiling effect (see Discussion) are denoted by *crosses*. A great propensity for head movement is indicated by high values of head gain and low values of COMR. (**A**) Horizontal head gain versus horizontal field of view. (**B**) Vertical head gain versus vertical field of view. (**C**) Horizontal COMR versus horizontal field of view. (**D**) Vertical COMR versus vertical field of view. (**E**) Horizontal head gain versus age. (**F**) Vertical head gain versus age. (**G**) Horizontal COMR versus age. (**H**) Vertical COMR versus age.

these studies may be limited by small sample sizes. The laboratory-based tasks in the present study were highly repeatable, and the comparatively larger sizes of the early-moderate RP and control groups allowed for statistical analyses that controlled for field of view and age.

There was considerable variation in head movement propensity between individuals, even accounting for the effects of age, group, and visual field extent. This is consistent with previous studies in normal-sighted participants by Thumser et al.[18] and particularly Fuller,[20] who classified participants as "head movers" and "nonmovers." Variation among the RP group also may be partly explained by a greater capacity for compensatory gaze strategies in some individuals, as previously demonstrated in hemianopic patients.[21,22]

Age Correlated With Increased Head Movement Propensity

Other studies have investigated the effect of age on head movement propensity. Our own results mirror those of Proudlock et al.,[12] who reported that horizontal smooth pursuit head gain was greater in individuals older than 60 years old compared with those younger than 60 years old, with greater intersubject variability in the older group. A later study

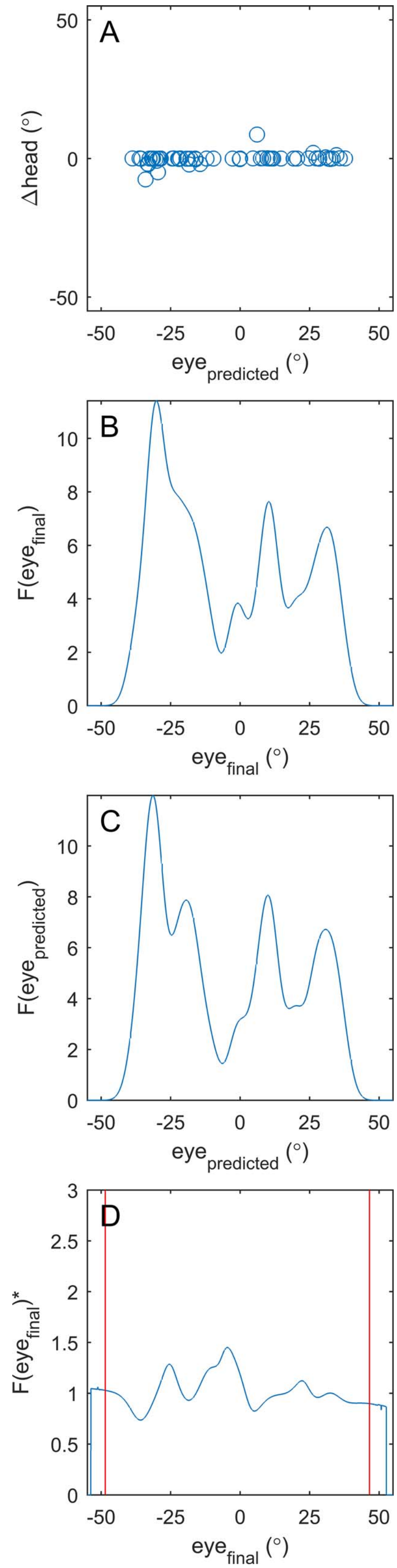

FIGURE 9. An example of COMR derivation for a participant who made very little head movement during the horizontal saccade task. (**A**) *Δhead* against $eye_{predicted}$ is flat and lacks the characteristic sloping lobes of Figure 6A. This is likely because the saccade targets were not eccentric enough to evoke head movements in this individual (**B**). Frequency of occurrence of eye_{final}. (**C**) Frequency of occurrence of $eye_{predicted}$. (**D**) Normalized frequency of occurrence of eye_{final}. The distribution is abruptly truncated and lacks the smoothly tapered edges of Figure 6D. The COMR (*red lines*) encloses 90% of the area under the curve.

TABLE 3. Summary of Results of a General Linear Model on HHG and VHG and Customary Oculomotor Range (VCOMR, HCOMR) With Group as a Factor and Age as a Continuous Predictor

	Model, Age, Group			
Measure	**$F_{2,34}$**	**Model *P***	**Factor**	**Factor *P***
HHG	22.16	< 0.001***	Age	< 0.001***
			Group	0.040*
HCOMR	5.82	0.007**	Age	0.024*
			Group	0.017*
VHG	21.53	< 0.001***	Age	< 0.001***
			Group	0.026*
VCOMR	7.11	0.003**	Age	0.007**
			Group	0.018*

The results of an F-test demonstrating improvement over the null model are presented, along with *P* values for each predictor included in the model. Significant results are denoted by asterisks (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$). Age and group both had a significant effect on HHG and VHG and COMR.

by Thumser et al.[18] found no effect of age on horizontal COMR. Thumser et al.[18] attributed this to their stimulus paradigm (originally described by Stahl[13]), which includes measures to discourage participants from modifying their behavior to the specific task, namely their use of a wide range of target eccentricities, randomized target locations, and "perisaccadic targets." They propose that their own results reveal an "underlying mechanism" of eye-head coordination, whereas the results of Proudlock et al.[12] reveal a greater capacity for modified gaze behavior in the younger subjects, who recognized that it was more efficient to complete the specific task with eye movement only. Two findings from the same group support this argument: the expectation of future gaze shifts in any particular direction can influence eye-head coordination,[23] and COMRs measured in a laboratory-based saccade task correlate well with the "outdoor COMR" measured during a passive viewing task in a naturalistic setting.[24]

Considering the similarity between our result and that of Proudlock et al.,[12] the predictable nature of our stimuli (no peri-saccades, predictable target locations/paths), which was necessary to accommodate low-vision participants, may have encouraged modified gaze behavior. We should interpret the results in this light and consider the measured head-gains and COMRs as task-specific. However, the "underlying" behavior, although interesting from a vision neuroscience perspective, is not necessarily clinically useful if that behavior is then modified to suit whatever task is at hand. We also note the similarity between the to-and-fro motion of gaze produced by both of the tasks in this study and the scanning that RP patients are encouraged to use when navigating. Our results are representative of the eye-head coordination of the participants while scanning to-and-fro and their ability to adapt their eye-head coordination to the task.

Implications for Visual Prostheses

Visual prostheses are implantable medical devices that aim to provide artificial vision to the blind.[25] Retinal implants are the predominant form of visual prosthesis, and are typically

TABLE 4. Summary of Results of a General Linear Model on HHG and VHG and VCOMR and HCOMR With Age and Field of View Extent as Continuous Predictors

	Model, Age, FoV			
Measure	$F_{2,34}$	Model *P*	Factor	Factor *P*
HHG	23.34	< 0.001***	Age	< 0.001***
			HFoV	0.022*
HCOMR	6.63	0.004**	Age	0.027*
			HFoV	0.008**
VHG	21.96	< 0.001***	Age	< 0.001***
			VFoV	0.031*
VCOMR	7.33	0.002**	Age	0.010*
			VFoV	0.013*

The results of an F-test demonstrating improvement over the null model are presented, along with *P* values for each predictor in the model individually. Significant results are denoted by asterisks (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$). Age and field of view both had a significant effect on HHG and VHG and COMR.

implanted in patients with end-stage RP. One of the major challenges faced by users of visual prostheses (with the exception of photodiode-based devices) is scanning of the visual environment. Eye position is decoupled from the orientation of the camera, interfering with the user's perception of space and visual constancy, and forcing the user to rely entirely on head movement for visual scanning.[26] Gaze contingent systems that restore the coupling of eye position and gaze have been shown to improve hand-eye coordination in simulation[27] and in Argus II recipients,[28] but have not yet reached regulatory-body–approved devices. The participants in the present study are not necessarily representative of present-day retinal implant recipients, who are typically in end-stage RP. Nevertheless, those involved in the design or psychophysical evaluation and fitting of visual prostheses should consider that the eye-head coordination strategies of their patients may have been affected by their condition, and are likely to vary significantly between individuals. The trends observed in the present study suggest that candidates for implantation would exhibit a significantly greater propensity for head movement.

Limitations

Four early-moderate RP patients (22%) and nine healthy sighted controls (47%) completed the saccade task with very little head movement, leading to a ceiling effect on COMR. In these cases, the true COMR is likely to be higher than the reported value. However, because the control group, which had a greater average COMR, was disproportionately affected, we find it unlikely that this would alter the main findings of the study. Repeating the analysis using the true values for those participants would most likely yield a more pronounced difference between the two groups. Future studies should include targets at greater eccentricities to ensure head movements are evoked in all participants (for example, Stahl[13] used targets at eccentricities up to $\pm 55°$).

Visual fields for the control participants were assumed within healthy limits and ascribed a representative value of $200 \times 135°$ following confrontation testing and retinal examination.[17] Given that optometric testing did not reveal any signs of retinal or optic nerve disease in any control participants and only very small changes in visual field are expected with age,[29] we find it unlikely that imprecision in this visual field estimate would significantly affect our findings. This was confirmed by a Monte Carlo simulation in which the horizontal and vertical fields of view of control participants were drawn from a bivariate normal distribution and the statistical analyses were repeated ($n = 5000$, $\mu_x = 200$, $\mu_y = 135$, $3\sigma_{xy} = 14°$, chosen because PVFL can be defined as HFoV $<186°$).[30] In 99.0% of simulations, the findings of the present study were reaffirmed.

It is not clear to what extent results from the present study's highly synthetic tasks with limited field of view are generalizable to real-word conditions, but laboratory-based COMR has been shown to correlate well with "outdoor COMR" measured during passive viewing in a naturalistic setting.[24] In the only study to our knowledge that has commented on both eye and head movement in PVFL, Authié et al.[7] showed that during locomotion, head position was more variable in RP than in controls, but eye position variability was similar. This result is congruent with our results, showing an increased propensity for head movement in RP.

CONCLUSIONS

RP is associated with an increased propensity for head movement during gaze shifts, and the magnitude of this effect is dependent on the degree of visual field loss. Age was also associated with increased propensity for head movement; however, variation between individuals was high and dominated the effects of visual field loss and age.

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