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Monocular and binocular smooth pursuit in central field loss

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ABSTRACT

Macular degeneration results in heterogeneous central field loss (CFL) and often has asymmetrical effects in the two eyes. As such, it is not clear to what degree the movements of the two eyes are coordinated. To address this issue, we examined smooth pursuit quantitatively in CFL participants during binocular viewing and compared it to the monocular viewing case. We also examined coordination of the two eyes during smooth pursuit and how this coordination was affected by interocular ratios of acuity and contrast, as well as CFL-specific interocular differences, such as scotoma sizes and degree of binocular overlap. We hypothesized that the coordination of eye movements would depend on the binocularity of the two eyes. To test our hypotheses, we used a modified step-ramp paradigm, and measured pursuit in both eyes while viewing was binocular, or monocular with the dominant or non-dominant eye. Data for CFL participants and age-matched controls were examined at the group, within-group, and individual levels. We found that CFL participants had a broader range of smooth pursuit gains and a significantly lower correlation between the two eyes, as compared to controls. Across both CFL and control groups, smooth pursuit gain and correlation between the eyes are best predicted by the ratio of contrast sensitivity between the eyes. For the subgroup of participants with measurable stereopsis, both smooth pursuit gain and correlation are best predicted by stereoacuity. Therefore, our results suggest that coordination between the eyes during smooth pursuit depends on binocular cooperation between the eyes.

1. Introduction

Central field loss (CFL) due to diseases such as macular degeneration presents a complex challenge, as well as a unique opportunity, to look at how damage to the retina affects vision and oculomotor behaviors. The pattern of vision loss in CFL is highly heterogeneous. For a given eye, the degree of disease progression, the exact shape and distribution of the damage (scotoma), and placement of the preferred retinal locus (PRL) vary tremendously across individuals with CFL (Fletcher & Schuchard, 1997). Previous literature has shown that looking at this array of characteristics is important for understanding visual performance in this population (Fletcher & Schuchard, 2006). In a recent paper we looked at how these characteristics affect smooth pursuit in individuals with CFL (Shanidze, Fusco, Potapchuk, Heinen, & Verghese, 2016) during monocular viewing. However, changes in monocular versus binocular gaze have been shown previously (Kabanarou et al., 2006), and the problem is further complicated by differences in scotoma and PRL characteristics between eyes for a given individual. Some individuals exhibit overlapping scotomata and PRLs that are placed symmetrically, which result in a binocular scotoma that closely resembles the scotomata in each eye. Others develop the disease in one eye and the other eye is able to compensate for the majority of the visual field loss. Most often, however, individuals with CFL have an intermediate situation where each eye has some degree of field loss that is partially overlapping between the two eyes, but even the degree of overlap can vary, depending on the number and placement of the PRLs in each eye (Tarita-Nistor, González, Markowitz, & Steinbach, 2006). These losses in foveal vision result in oculomotor behaviors that are distinct from the fovea-based, symmetric, binocular vision-driven behaviors that have been studied in human and non-human primates for decades previously.

This continuum of differences in patterns of vision loss presents a challenge to understanding behaviors that are normally binocular and may rely on the use of the central retina and specifically the fovea, such as smooth pursuit. Smooth pursuit is used to stabilize a moving stimulus on the retina and in the case of a spot stimulus, the fovea closely tracks the moving target (for review see Krauzlis, 2004). As such, in individuals with normal vision, smooth pursuit eye movements are likely conjugate during binocular tracking in the fronto-parallel plane, with the foveas of both eyes following the object of interest. It is not clear how this behavior might change if the fovea in either, or both eyes is no longer avail-

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able and the new PRLs may not be in retinal correspondence. A simple hypothesis would be that smooth pursuit would be driven entirely by the dominant, or better eye. However, individual differences in this population complicate this interpretation – the definition of a "better" eye may change depending on the task at hand. For example, an individual with a ring-shaped scotoma may use the eye with higher acuity for reading, but may use the other eye for more global processing. Another possibility is that both eyes are utilized for pursuing a moving target, with each eye compensating for physiological limitations on the other's movement; because PRL location can be highly eccentric, the eye may be limited in how much it can move in the orbit and therefore both eyes may be necessary to follow the target, taking over at different parts of the trajectory.

In this study, we examined characteristics of binocular smooth pursuit eye movements in response to a single spot target moving in the fronto-parallel plane. We examined binocular and monocular viewing in individuals with central field loss and age-matched controls with healthy vision. We hypothesized that participants with CFL would have reduced coordination between the two eyes during monocular and binocular viewing, as compared to controls, with the dominant eye driving the smooth pursuit behavior. To test our hypotheses, we used several levels of analysis, starting by comparing CFL and control participants, then examining trends within the CFL group, and finally looking at individual differences on a participant-by-participant basis. Consistent with our hypothesis, we found reduced correlation in the movement of the two eyes in CFL individuals, as compared to controls, that was especially evident during viewing with the non-dominant eye. Smooth pursuit gains were also affected across viewing conditions, with worst gains and highest gain discrepancies between the two eyes occurring during non-dominant eye viewing. Participants' ratio of contrast sensitivity between the eyes and stereoacuity had significant effects on both between-eye correlations and monocular smooth pursuit gains.

2. Materials and methods

2.1. Participants

All research was performed in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of the Smith-Kettlewell Eye Research Institute. We recruited 7 participants with central field loss (ages: 52–91, 4 males) and 4 controls (ages: 70–84, 1 male). All participants provided informed consent. All controls had no vision or eye movement disorders. All CFL participants had macular degeneration (6 with age-related macular degeneration and 1 with Stargardt's disease, P2) in one or both eyes. One CFL participant also had a history of strabismic amblyopia, with a dominant fellow eye (P5, Table 1).

Prior to testing, all participants were assessed using a standard battery of tests to calculate their acuity, contrast sensitivity, and stereoacuity. Scotomata were mapped monocularly using standard microperimetry approaches in the scanning laser ophthalmoscope (Optos OCT/SLO) and fixational stability was measured as the 68% bivariate contour ellipse area (Steinman, 1965) during a 10-s fixation task. To estimate binocular scotoma areas, we used an in-house algorithm (Ghahghaei & Walker, 2016) that allowed us to combine the monocular maps using the optic disc and the foveal pits (if available from the OCT) or an estimate of the foveal location based on normative data of foveal location from the center of the optic disc (Kabanarou et al., 2006). The amount of scotoma overlap was estimated statically for straight ahead gaze. Ocular dominance was assessed using Miles' "hole-in-the-hand" method (Roth, Lora, & Heilman, 2002).

2.2. Equipment

Participants were seated 1 m away from a CRT monitor. Each participant's head was restrained comfortably in a chin and forehead rest, and eye movements were recorded using an Eyelink 1000 infrared eye tracker, placed in the table-top configuration, to allow for binocular tracking. Data were sampled at 1000 Hz. During experimental blocks with monocular viewing, participants wore an opaque eye patch (transparent to infrared) over the non-viewing eye. Calibration was performed at the beginning of each block, which consisted of 90 trials of the same viewing condition: binocular, monocular left, and monocular right.

2.3. Smooth pursuit

For each trial, participants viewed a 1° white annulus (0.2° black center) that appeared in the center of a black screen, and were asked to follow a target that moved in a modified step-ramp paradigm (Rashbass, 1961). Participants initiated each trial with the press of the space bar. Trial onset was gaze-contingent, requiring the participant to fixate within 3–5° of screen center (to allow for fixational instability due to CFL participants' eccentric viewing) for 0.3 s plus a random delay period between 500 and 1000 ms. Once fixation was acquired for a requisite amount of time, the central target disappeared and reappeared at one of six possible locations, 6° from center. The target then moved in the opposite direction of the initial step (0°, 90°, 135°, 180°, 270°, 315°) for 12°, moving through screen center. Targets moved at one of three possible velocities (5, 10, 15°/s), and each velocity and trajectory combination was repeated 5 times, for a total of

Table 1

Participant demographics: Dx – Diagnosis (CFL Status), CS – contrast sensitivity, SA – stereoacuity, B – binocular, D – dominant eye, ND – non-dominant eye, R – right, L – left.

ID	D Eye	Age	Sex	Dx	logMAR Acuity (D)	Acuity (D/ND)	MARS CS (D)	MARS CS (D/ND)	SA (arcmin)	Fixational stability (D)	Fixational stability (D/ND)	Scotoma area (D/ND)	Scotoma overlap (B/D)
P1	R	73	M	AMD	1.3	0.097	1.05	1.4	10	0.5	0.455	1.08	0.67
P2	R	52	M	JMD	−0.1	0.000	1.6	1.08	5	0.8	1.333	1.10	0.78
P3	R	71	M	AMD	0.1	1.000	1.8	1.15	>30	1	0.714	0	–
P4	R	87	F	AMD	0.7	0.302	0.88	0.66	>30	0.6	0.545	1.60	0.22
P5	L	91	M	AMD	0.1	4.805	1.2	2.88	>30	0.3	0.057	0.52	0.61
P6	L	84	F	AMD	0.6	0.574	1.02	2.13	13.33	0.4	0.235	0.53	0.41
P7	R	87	F	AMD	0.2	0.097	1.08	1.35	>30	1.3	1.000	3.14	0.26
C1	L	84	F	Control	−0.1	0.097	1.72	0.93	0.67	0.1	1.000	–	–
C2	L	70	F	Control	0.0	0	1.72	1.02	0.67	0.1	2.000	–	–
C3	R	73	F	Control	−0.1	0.097	1.76	1.00	0.1	0.1	1.000	–	–
C4	L	74	M	Control	0.1	0	1.76	1.00	1	0.05	0.500	–	–

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