

Visual Field Dependence Persists in Age-Related Central Visual Field Loss

Catherine P. Agathos and Natela M. Shanidze

The Smith-Kettlewell Eye Research Institute, San Francisco, California, United States

Correspondence: Catherine P. Agathos, The Smith-Kettlewell Eye Research Institute, 2318 Fillmore, San Francisco, CA 94115, USA; cagathos@ski.org.

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PURPOSE. To examine whether the age-related increase in visual field dependence persists in older adults with central field loss (CFL).

METHODS. Twenty individuals with CFL were grouped into participants with age-related binocular CFL (CFL, $n = 9$), age-related monocular CFL/relative scotomata (mCFL, $n = 8$), and CFL occurring at a young age (yCFL, $n = 3$). Seventeen controls were age-matched to the older CFL groups (OA) and three to the yCFL group (yOA). Participants judged the tilt direction of a rod presented at various orientations under conditions with and without a visual reference. Visual field dependence was determined as the difference in judgment bias between trials with and without the visual reference. Visual field dependence was examined between groups and relative to visual acuity and contrast sensitivity.

RESULTS. All older groups performed similarly without the visual reference. The CFL group showed greater visual field dependence than the OA group (Mann-Whitney U test; $U = 39$, $P = 0.045$). However, there was no group difference when considering all three older groups (Kruskal-Wallis ANOVA; $H(2, N = 34) = 4.31$, $P = 0.116$). Poorer contrast sensitivity correlated with greater visual field dependence ($P = 0.017$; $\rho = -0.43$).

CONCLUSIONS. Visual field dependence persists in older adults with CFL and seems exacerbated in those with dense binocular scotomata. This could be attributed to the sensitivity of the spared peripheral retina to orientation and motion cues. The relationship with contrast sensitivity further suggests that a decline in visual function is associated with an increase in visual field dependence beyond the effects of normal aging. These observations can guide tailored care and rehabilitation in older adults with CFL.

Keywords: central visual field loss, macular degeneration, visual field dependence, aging, subjective visual vertical

Age-related macular degeneration (AMD) is associated with loss of central retinal (macular) function in older age. It is one of the most common forms of visual impairment in older adults and a leading cause of irreversible vision loss in industrialized countries.¹ Loss of central vision leads to decreased visual acuity, contrast sensitivity, loss of depth perception, and visual field defect due to the resultant scotoma, particularly when the deficit is binocular. Interestingly, loss of vision in AMD co-occurs with aging, when people are increasingly more reliant on visual information for the assessment of one's own and external objects' position, orientation, and movement.²⁻⁵

Normal aging entails impairment in multiple sensory, motor, and cognitive systems, all of which contribute to mobility decline⁶ that can limit individuals' autonomy and increase fall risk.^{7,8} Moreover, safety and mobility rely on the accurate perception of one's surroundings and their movement through the world, which requires the appropriate combination of separate sensory/motor information streams. Visual, vestibular, and somatosensory (proprioceptive and tactile) inputs must be integrated and optimally (re)weighted depending on signal reliability^{9,10} and environmental and task demands.⁹ At the same time, how these signals are reweighted and integrated to perceive and inter-

act with the environment also depends on one's mode of spatial referencing¹¹—that is, aligning the body within a gravito-inertial field or on surrogates of the direction of gravity, such as the support surface or axes within the visual field (e.g., walls, ground, lampposts). Aging affects sensory integration of multiple modalities,^{6,12} with a greater weighting of visual information in older age,^{3-5,13} likely associated with age-related declines in other sensory systems^{14,15} that are more severe and/or occur earlier than visual aging.^{16,17} Problematically, this increase in visual field dependence may lead to various postural and walking issues, such as alterations in body coordination,¹⁸⁻²⁰ adaptation difficulties,^{3,21} and falls,²²⁻²⁴ which can, in turn, lead to mobility limitations. Moreover, when individuals rely more on visual information while interacting with their environment, they are more affected by perturbations in the visual field.^{5,25,26} In real-life settings, visual field perturbations could be due to a sudden change of luminance when transitioning from an indoor to an outdoor environment or the strong visual motion stimulus from a large vehicle passing by. These limitations may be even more debilitating when visual information is altered/unreliable, as in the case of central field loss (CFL), such as that due to AMD.



In this study, we hypothesized that the age-related increase in reliance on visual cues is not reduced in AMD, given that (1) age-related sensorimotor deficits are ubiquitous in aging, and (2) the peripheral retina is largely spared in macular degeneration. If visual field dependence indeed persists with AMD, this could be maladaptive, as affected individuals are relying more on the sense that is failing them. We tested our hypothesis using psychophysical tests of subjective visual vertical (SVV) estimation (akin to the widely used rod and frame test),^{13,27} where the extent to which an individual is influenced by the presence of a visual reference frame indicates their level of visual field dependence. Here, we used this approach to test whether visual field dependence in those with AMD would indeed be comparable to or even greater than their visually healthy peers.

METHODS

Participants

All screening and experimental procedures were conducted in accordance with the tenets of the Declaration of Helsinki and approved by the Institutional Review Board of the Smith-Kettlewell Eye Research Institute (SKERI). All participants provided informed, written consent to participate in the study and were compensated for their time.

Participants included 20 older adults with CFL and 20 visually healthy older adults. Those with CFL consisted of nine individuals with binocular CFL (CFL; six females; 79.8 ± 6.2 years old, range: 70–88 years) and eight individuals with monocular CFL or non-overlapping/relative scotomata in the two eyes (mCFL, four females, 75.8 ± 4.8 years old, range: 68–84 years) for whom the deficit occurred in older age. Three additional individuals had a juvenile form of macular degeneration resulting in a binocular scotoma (yCFL; all males, 62 years old). The Table provides demographic and visual pathology information for the participants with CFL. Eight participants were tested at SKERI and 12 were tested at the Envision Research Institute (ERI, Wichita, KS, USA). Of the 20 visually healthy older adults, 17 were age matched, on average, to the older patients with CFL (OA; eight males, 76.6 ± 3.7 years old, range: 71–84 years; one-factor ANOVA, $P = 0.168$) and three to the yCFL group (yOA; two males, 63.3 ± 2.9 years old, range: 60–65 years). All control participants were tested at SKERI.

Given that the SVV tasks relate to individuals' interaction with the environment and use large (well above threshold) stimuli, participants were instructed to wear or remove their visual correction according to how they behave when moving about in daily life. As such, the visual function measures reported here and used for analysis correspond to the testing conditions. Visual acuities and contrast sensitivity thresholds for individuals with CFL are provided in the Table. For the control group, mean visual acuity was 0.15 ± 0.12 logMAR, and contrast sensitivity (CS) was 1.7 ± 0.13 logCS. We were not able to obtain visual acuity for one older CFL (OA) participant and contrast sensitivity for two OA participants. Where available, we provide binocular visual acuities (CFL7–CFL9, mCFL4–mCFL8, yCFL3, and 17 controls); the rest are for the better eye. The blind Montreal Cognitive Assessment (MoCA)²⁸ was used for cognitive screening of participants over 65 years old. Monocular microperimetry was performed to establish CFL in all visually impaired participants; we used the iCare MAIA SLO (Icare Finland Oy, Vantaa, Finland) for those tested at












ERI and one participant at SKERI and the OptosOCT/SLO (Optos, Inc., Marlborough, MA, USA) for the other seven at SKERI. Binocular scotomata estimates are provided in the Table for participants with binocular CFL where available. These are based on the central tangent field method²⁹ for those tested at ERI. At SKERI, the binocular scotomata were assessed using the method in (Vullings and Verghese, 2021).³⁰

Experimental Set-Up and Stimulus Presentation

In both lab settings, participants sat comfortably in a chair with their head restrained by a chin and forehead rest (Fig. 1A). Stimuli were presented in complete darkness on a large screen at 60 cm, viewed through an optic tube hanging from the ceiling (45.5 cm length, 35.5 cm in diameter) providing a visual field of 59.5° of visual angle. The visual stimuli were presented using custom software (Psychtoolbox for MATLAB; MathWorks, Natick, MA, USA) and consisted of a fixation target and a tilted line (rod length: 16.9 cm/ 16° at 60 cm) appearing either by itself or surrounded by a field of moving dots (a planar optic flow stimulus). This optic flow stimulus was chosen to provide a misleading (misaligned from vertical) visual reference for orientation (similar to the visual references in the rod and frame or rod and disc tests).^{4,31} The dots had a random spatial distribution and moved across the screen at $10^\circ/\text{s}$ in a linear trajectory rotated 15° clockwise or counterclockwise from Earth vertical (Fig. 1B). The dots covered the entire visible visual field, except for a central blank region 19 cm in diameter (18°) where the rod was presented. This blank region was included to prevent crowding effects between the central rod and moving dots, as in studies employing the rod and disc test.^{4,31} The full-field nature of the optic flow stimulus ensured that those with vision loss could perceive it regardless of the size or location of their scotoma. From here on, we refer to this optic flow stimulus as the “visual reference.”

The rod was presented at a range of orientations that was customized for each participant. Prior to testing, participants were provided with at least 24 practice trials (more if necessary) to familiarize themselves with the procedure and for the experimenter to obtain a rough estimate of their bias in orientation judgment. During these practice blocks, the range was set to $\pm [0.25^\circ \ 0.5^\circ \ 2^\circ \ 4^\circ]$ when the rod appeared on its own, and $\pm [0.5^\circ \ 1^\circ \ 2^\circ \ 4^\circ \ 8^\circ]$ when the rod appeared with the visual reference (optic flow stimulus). The rod orientation ranges were then adjusted to each participant's judgment bias, estimated during successful practice trials. When these practice-trial-based biases fell within 2° , a finer sampling was made near zero: $\pm [0.25^\circ \ 0.5^\circ \ 1^\circ \ 2^\circ]$ with larger orientations added in increments of 2° . To limit the test duration of each test condition block (no visual reference, with clockwise and counterclockwise tilted reference), there were a maximum of 14 orientations, given that each rod orientation was repeated 10 times in random order during each test block. If a good fit was not achieved to estimate a participant's point of subjective equality (see Dependent Variables section below), the block was repeated with a wider range of rod orientations (the maximum in our study being $\pm 24^\circ$). In such cases (12 across participants and conditions), where a block was repeated, the increments between larger orientations were increased to 4° or 6° to ensure that the participant's entire psychometric range was covered and to minimize the number of trials needed. The performance at all

TABLE. CFL Participant Demographics and Visual Function

ID	Age	Sex	Diagnosis	Visual Acuity (logMAR)	Log Contrast Sensitivity	Binocular Scotoma Estimate*	Testing Site
CFL1	71	M	AMD	1.80	Not Available		ERI
CFL2	88	M	AMD	0.84	1.30		ERI
CFL3	70	F	Plaquenil maculopathy	0.53	2.00		ERI
CFL4	81	F	AMD	0.42	1.30		ERI
CFL5	88	F	AMD	1.28	1.00		ERI
CFL6	78	M	AMD	1.06	1.30		ERI
CFL7	81	F	AMD	0.68	1.50		SKERI
CFL8	82	F	AMD	0.32	1.36	Not Available	SKERI
CFL9	80	F	AMD	0.04	1.40		SKERI
mCFL1	75	F	Diabetic Retinopathy with Macular Edema	0.62	1.30	N/A	ERI
mCFL2	79	M	AMD	0.30	1.70	N/A	ERI
mCFL3	84	F	AMD	0.86	1.70	N/A	ERI
mCFL4	72	M	AMD (OU, non-overlapping)	0.02	1.00	N/A	ERI
mCFL5	78	M	AMD (OS)	0.10	1.68	N/A	SKERI
mCFL6	68	M	AMD (OD)	0.24	1.36	N/A	SKERI
mCFL7	76	F	Macular hole (OD)	Not Available	1.44	N/A	SKERI
mCFL8	74	F	AMD (OU, non-overlapping)	0.30	1.68	N/A	SKERI
yCFL1	62	M	Stargardt's	1.30	1.30		ERI
yCFL2	62	M	Stargardt's	1.30	1.30		ERI
yCFL3	62	M	Stargardt's	0.94	0.95		SKERI

N/A, not available; OD, right eye; OS, left eye; OU, binocular.

*The available scotoma estimate for each participant is depicted on a circular grid of 10° radius (each ring is separated by 2.5°), centered on each participant's fixation.

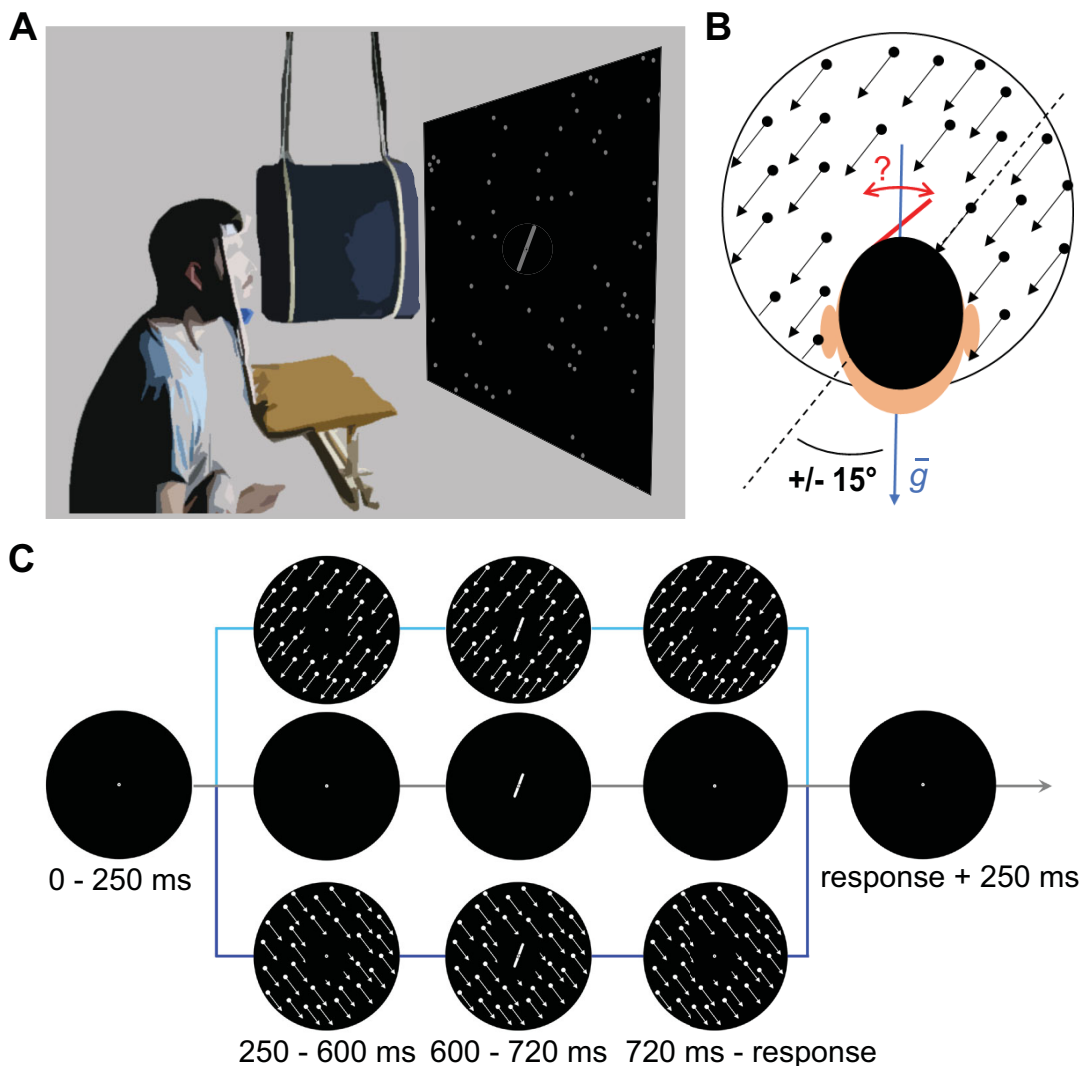


FIGURE 1. Schematic of the experimental setup and procedure. (A) The participant viewed the screen through an optic tube suspended from the ceiling (44.5×35.5 cm; field of view, 59.5°); the condition with the optic flow stimulus (visual reference) is shown. The head was restrained using a forehead and chin rest. (B) Participant's view of the experimental stimuli in A. A tilted rod (shown as a red line, but normally the same color as the dots) flashed briefly, and participants had to indicate by button press whether it was tilted clockwise or counterclockwise with respect to vertical (illustrated by the blue gravity vector). The rod and tube are not drawn to scale. The stimulus and background colors are inverted, and dot motion is shown with arrows for illustration. (C) Experimental trial structure with the three trial types: clockwise visual reference (top), no visual reference (middle), or counterclockwise visual reference (bottom). The trial started with a presentation of a fixation target (250 ms), followed by a priming period (350 ms) before the tilted rod appeared for 120 ms. After an unconstrained response duration, a 250 ms between-trial period followed where only the fixation dot was shown. In the conditions with visual reference, the moving dots appeared during the priming period, rod presentation, and response duration. The order of conditions was randomized for each participant.

tested orientations was used in the probit fit, which weighted the data at each orientation by the number of trials presented at that orientation. The test block order (no visual reference, with clockwise, or counterclockwise tilted visual reference) was randomized for each participant.

All stimuli were presented slightly larger for participants with macular pathologies versus controls: 2° versus 0.8° for the fixation target, 1° versus 0.6° for the rod width, and 1° versus 0.8° for the visual reference dots. All stimuli were light gray on a black background, with a Weber contrast of 13. Participants logged their responses using a small, two-button USB keyboard held in their lap that was connected to the stimulus computer.

Procedure

Prior to testing, participants were briefed about the procedure and were given as much practice time as necessary to become familiar with the display and the keyboard response method. They were instructed to indicate (via a left- or right-button keypress) the direction in which the tilted rod appeared with respect to vertical, as described previously.^{13,27} Participants were given three examples of verticality to guide their responses: visual vertical (wall ridges or door frames), gravitational vertical (space rocket or plumb line), and postural vertical (erect body). Participants were made explicitly aware of the fact that they controlled the

experimental pace; they started the block with a button press when ready to begin and could take as much time as necessary to provide their response after each rod presentation. Three built-in break periods divided the trial blocks into quarters, and participants could rest as long as desired. A message appeared indicating that participants should rest if they needed to, and when ready to start again they could press either button to continue.

The experimental sequence is shown in Figure 1C. First, the fixation target appeared for 250 ms (except at experiment initiation and after each break, where the fixation period was 1 second), followed by a priming period of 350 ms (displaying only the fixation target or both the target and optic flow dot field—the visual reference—according to the experimental condition), and the tilted rod presentation for 120 ms. Participants then indicated the perceived tilt direction of the rod (clockwise or counterclockwise) with a button press. A period of 250 ms between trials followed. The fixation target was always visible, and participants were instructed to try to maintain their gaze on it throughout the experimental blocks. All participants employed their habitual fixation locus, meaning that individuals with a binocular scotoma (CFL group) viewed the central target and rod eccentrically, with the central scotoma placed to the side of the stimulus. In the blocks containing the visual reference, this was present during the priming, rod presentation, and response intervals.

The experimenter checked the data after each block of trials to make sure the range of rod orientations was appropriate to obtain a full psychometric function of the orientation judgment. When necessary, the block was repeated to include a larger or finer range of rod orientation presentations. At the end of the experimental session, the experimenter asked the participants a series of questions to ascertain their subjective appreciation of the stimuli and potential strategies used to successfully complete the tasks.

Dependent Variables

The point of subjective equality, or orientation judgment bias, was estimated for each condition by fitting a generalized linear model with a probit link function (glmfit) to each participant's responses, using custom MATLAB software (see examples in Fig. 2). This bias is the orientation at which the participant can no longer tell whether the rod is tilted clockwise or counterclockwise with respect to vertical and is thus an estimation of their subjective visual vertical (SVV). Each participant's biases for all three conditions (no visual reference, clockwise reference, and counterclockwise reference) are shown in Supplementary Figure S1. The associated slope estimates of each participant's psychometric curve are shown in Supplementary Figure S2 for all three conditions.

In the condition without a visual reference, we took the absolute bias value to represent participants' SVV—that is, how much their representation of gravity deviated from true vertical irrespective of direction. Visual field dependence was quantified as the magnitude of the effect of the misleading visual reference (provided by the optic flow stimulus) on individuals' SVV. In other words, we calculated the change in SVV, or algebraic difference between conditions with and without the visual reference, similar to previous work.^{24,32} Briefly, we took the signed difference between the bias on the condition without the visual reference and on that with the reference (optic flow moving in either direction), and we

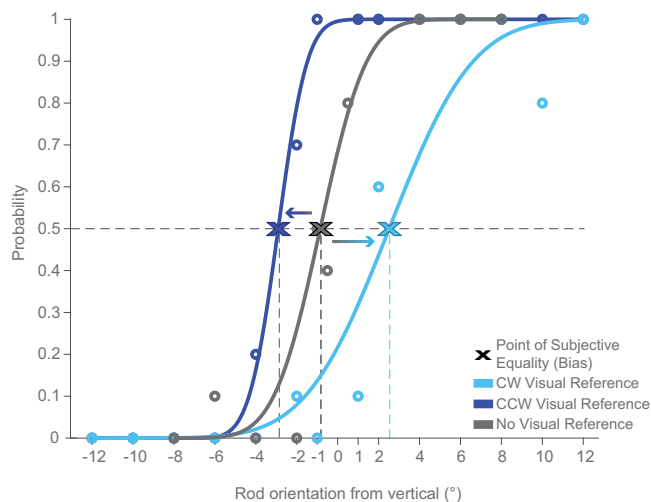


FIGURE 2. Example of data probability fit in each condition for a representative participant. Data from an older control participant are plotted for each condition (*dark gray*, no visual reference; *light blue*, clockwise reference; *dark blue*, counterclockwise reference). *Circles* indicate the probability of responding “clockwise” (right button press) for each rod orientation presented (with 1 being 100% likely). The S-curves indicate the fit for each condition from which the point of subjective equality, or bias (marked with an *x*), is determined (i.e., the value associated with each curve at 50% probability). In this example, the bias for each condition is -0.85° in the no reference condition, -2.90° in the counterclockwise condition, and 2.52° in the clockwise condition. To quantify individuals' SSVs, we took the absolute bias in the condition with no visual reference, thus reporting the size of the deviation of the individual's estimate from true vertical. *Arrows* illustrate the bias shift from the condition with no reference to those with the visual reference. The absolute difference or shift (3.37° and 2.05° , respectively) was averaged across the two visual reference conditions to obtain our measure of visual field dependence.

then averaged the absolute of these differences as follows:

$$\begin{aligned} \text{Absolute bias shift} \\ = \text{Average} (& | \text{Bias}_{\text{CW_reference}} - \text{Bias}_{\text{no_reference}} | , \\ & | \text{Bias}_{\text{CCW_reference}} - \text{Bias}_{\text{no_reference}} |) \end{aligned}$$

Statistical Analysis

Statistical analyses were performed using Prism 10 (GraphPad Software, Boston, MA, USA). Experimental data were checked for normality using the Shapiro–Wilk test. When normality was not met, non-parametric tests were used for analysis. As our hypothesis was based on total central vision loss, we first performed non-parametric group comparisons on the orientation judgment data between the older individuals with binocular central field loss and the older age-matched controls (Mann–Whitney *U* test). To obtain a broader understanding of how visual deficit affects spatial referencing, we also compared data from all three older groups (CFL, OA, and the mCFL group) using a Kruskal–Wallis ANOVA. Data from the two other groups (yCFL and yOA) are presented for illustrative purposes. They were not included in the group comparisons given the small sample sizes and the fact that vision loss in the yCFL group occurs prior to the age-related increase in visual field dependence.^{4,13,33} Correlations were performed between the measures of visual function (visual acuity and contrast sensi-

tivity) and visual field dependence (absolute bias shift) across older adults with and without CFL. The relationship between SVV with and without a visual reference was examined using correlation analysis across these participants. We also examined these relationships within each group separately. When the data were normally distributed, a Pearson correlation was performed, and a Pearson R is provided in the text; a ρ estimate is provided when data were not normally distributed, and a Spearman correlation was performed. Alpha level was set at 0.05.

RESULTS

We first estimated each participant's absolute bias in SVV for trials without the visual reference. This test is a measure of the vestibular (primarily)³⁴ and somatosensory contributions to one's internal representation of vertical.³⁵ We found no significant group difference between older adults with binocular CFL and the age-matched controls ($U = 68$; $P = 0.672$) (Fig. 3A), suggesting a similar degree of vestibular aging between the two groups and no effect of visual impairment on the perception of rod orientation alone. This result also held when including the mCFL group ($H(2, N = 34) = 0.45$; $P = 0.798$). Absolute biases of the two younger groups were also similar (medians: yOA, -0.88° ; yCFL, -0.85°).

Figure 3B shows the magnitude of the effect of the visual reference on individuals' SVV for all groups (i.e., their visual field dependence). This was defined as the absolute bias shift between conditions with and without the visual reference (see Methods). Visual field dependence was found to be greater in those with binocular CFL compared to controls (medians: 3.25° and 1.61° , respectively; $U = 39$; $P = 0.045$). No significant difference was found when also including the mCFL group ($H(2, N = 34) = 4.31$; $P = 0.116$). Median values for those in the mCFL group were close to those of the older control participants (mCFL, 1.51°).

The younger participants with CFL were examined separately given that their onset of CFL was at a young age, before the age-related changes in vestibular/somatosensory function and age-related increase in visual dependence, potentially altering the typical, age-related progression of the reweighting process. Consistent with this idea, those in the younger groups had smaller median bias shifts, which were similar regardless of vision loss (0.79° for the visually healthy younger seniors and 0.94° for those with CFL).

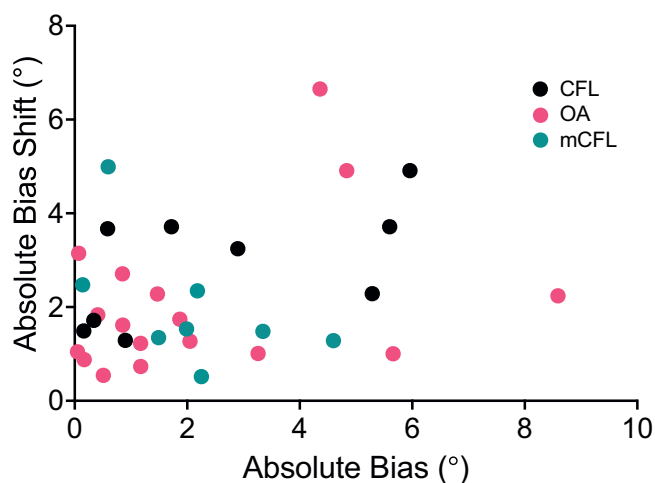


FIGURE 4. The relationship between bias on the SVV task without visual reference and SVV bias shift due to the added visual reference across older adults with and without CFL. The relationship did not reach significance when considering all data points, but we observed a trend for the older binocular CFL group ($P = 0.093$; $R = 0.59$).

Next, we examined if there was a predictive relationship between SVV biases without a visual reference and their shift due to the visual reference in all older participants (Fig. 4). There was no significant correlation across individuals from all three groups ($P = 0.164$; $\rho = 0.16$) but a stronger trend when considering only the binocular CFL group ($P = 0.093$; $R = 0.59$; regression: $y = 1.20x + 1.96$).

Finally, we examined whether decreases in visual function can predict an increase in visual field dependence in the same participants (Fig. 5). Across all groups, we found a significant negative correlation between contrast sensitivity and visual field dependence ($P = 0.017$; $\rho = -0.43$), indicating that those with worse contrast sensitivity (lower scores) are also more affected by the visual reference (larger absolute bias shift) (Fig. 5B). We observed a trend for the relationship between visual acuity and visual field dependence ($P = 0.056$; $\rho = 0.34$) (Fig. 5A), also suggesting that worse visual function may be associated with greater visual field dependence. When examining correlations for each group separately, we observed a strong trend between contrast sensitivity and visual field dependence for the CFL group ($P = 0.06$;

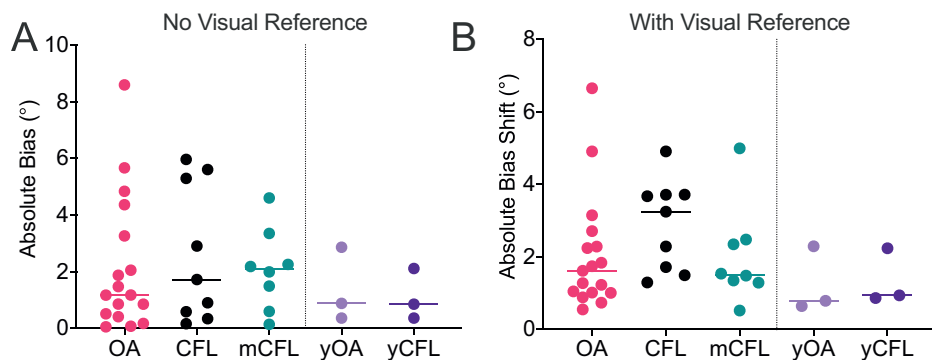


FIGURE 3. Group data on the SVV tasks. (A) Absolute bias in SVV estimation in the experimental block without the visual reference. (B) Absolute bias shift in SVV indicating the level of visual field dependence—calculated by taking the average absolute difference between bias in the conditions with and without the visual reference. Individual participant data are shown along with group medians (horizontal lines).

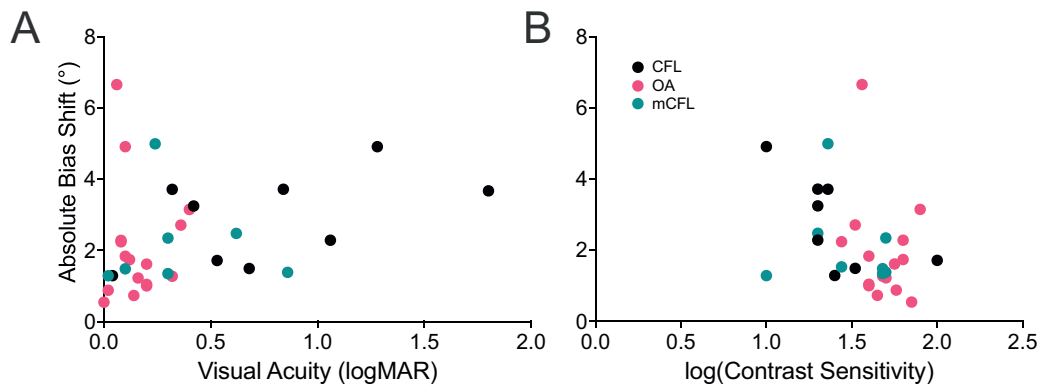


FIGURE 5. The relationship between visual function measures and visual field dependence across older adults with and without CFL. **(A)** There is a trend for the relationship between visual acuity and absolute bias shift across all three groups ($P = 0.056$; $\rho = 0.34$) but no notable relationship when considering each group individually. **(B)** There was a significant negative correlation with contrast sensitivity and absolute bias shift ($P = 0.017$; $\rho = -0.43$) across the three groups, and a trend for the CFL group ($P = 0.06$; $R = -0.69$). There was no significant relationship for the other two groups when considered separately.

$R = -0.69$; regression: $y = -3.14x + 7.18$). This relationship was non-significant for the other two groups (OA: $P = 0.442$, $\rho = -0.21$; mCFL: $P = 0.578$, $R = -0.23$). The correlations between visual acuity and visual field dependence did not reach significance for any individual group (OA: $P = 0.694$, $\rho = 0.11$; CFL: $P = 0.152$, $R = 0.52$; mCFL: $P = 0.630$; $R = -0.22$).

DISCUSSION

Visual Field Dependence in Older Adults With CFL

This study investigated whether the known age-related increase in visual field dependence persists in older adults with CFL. When examining only older adults with (overlapping) binocular CFL, we found that they are more influenced by an orienting visual reference than their visually healthy contemporaries. The difference between groups does not reach significance, however, when those with monocular CFL are also considered. Our findings are consistent with those of Radvay et al.,³⁶ who found no difference in visual field dependence with respect to age-matched controls. Notably, in that study, individuals with relative, absolute, and monocular scotomata were all pooled together. Additionally, we present a younger sample of individuals who developed binocular CFL in their youth and their age-matched controls—both groups were less influenced by the visual reference than the older participants. Although the younger groups had small sample sizes, these observations are in line with our suggestion that CFL does not lead to visual field dependence; rather, despite the degraded visual signal, visual field dependence persists (or is even exacerbated further) when CFL occurs in older age due to age-related deficits in sensorimotor systems, including sensory reweighting,^{6,12,37} and older adults' difficulties in switching to appropriate modes of spatial referencing.^{3,21,38}

It is well established that, with age, older adults increasingly rely on visual information to perceive their own and external objects' position, orientation, and motion.^{4,5,13,17,33,39–42} Why would older adults with CFL preferentially use visual information for spatial referencing given the less reliable visual input and potentially do so to a greater extent than their visually healthy peers? In young adults, such preferential reliance on a visual frame of refer-

ence is a manifestation of individual differences (or “perceptual style”),¹¹ but in older adults visual field dependence is also associated with age-related sensorimotor and cognitive decline.^{4,43} Our data indicate that even a decline in visual perception does not prevent older individuals from using visual cues as a frame of reference when experiencing similar changes in vestibular/somatosensory function as their healthy-sighted peers (indicated by similar performance on the SVV test without a visual reference^{34,35,44}). The lack of a significant correlation between individuals' biases with and without the visual reference further suggests that the greater visual field dependence is not driven by vestibular deficit.⁴⁵ The fact that a trend exists for those with binocular CFL, however, may indicate that these individuals might have a stronger reweighting response with the effects of vestibular aging—an important future direction for this work.

Association of Visual Field Dependence to Visual Function

To better understand the relationship between central vision loss and visual field dependence, we analyzed visual field dependence with respect to measures of visual function across our three main groups (CFL, mCFL, and OA). We found a significant correlation between contrast sensitivity and visual field dependence and a strong trend with visual acuity. These findings reflect the different nature of “preferred spatial referencing” in older versus young adults, whereby reliance on the visual reference frame in older age does not mean an optimal processing of visual information. Indeed, in visually healthy individuals, visual field dependence has previously been linked to reduced visual attention⁴ (as measured on the useful field of view test).⁴⁶ The stronger relationship between contrast sensitivity and visual field dependence (vs. visual acuity) is unsurprising given that contrast sensitivity is a better predictor of performance on everyday tasks, including mobility.^{47–51}

Peripheral Retinal Function as a Mediator of Visual Field Dependence

The peripheral retina is sensitive to dynamic visual cues and cues relating to spatial orientation, which are important

for motion perception,^{52,53} spatial orientation,⁵⁴ self-motion perception,⁵⁵ and dynamic balance.^{56–58} Further, orienting visual cues either lie in or extend to the peripheral visual field, which is largely spared in AMD. We therefore hypothesized that equivalent/increased reliance on the visual reference (a dynamic visual orienting cue) would be found in older adults with CFL. Although we expect to obtain similar findings using static visual orienting cues as a visual reference (as shown previously in older adults),^{4,13} whenever observers move through space, they experience visual motion, especially in the peripheral visual field. Thus, the optic flow stimulus chosen here as a visual reference is ecologically relevant to locomotor stability and relevant to real-world behavior. Studies examining motion perception (in terms of both threshold and direction detection) have found similar performance in older adults with and without CFL.^{53,59} Loss of the central visual field, therefore, does not limit (or enhance) individuals' ability to accurately detect and process visual motion, although it also does not appear to enhance these functions. Others have found a similar degree of vection—the feeling of self-motion induced by dynamic visual cues—in both eyes of individuals with monocular CFL⁶⁰ and between individuals with and without CFL.⁶¹ The latter study did observe shorter latencies in those with CFL for roll vection,⁶¹ whereas others have observed greater vection strength in individuals with CFL as compared to healthy controls.⁶² These studies, together with our findings, suggest that for older adults with CFL (and potentially, with increasing severity) residual vision from the intact peripheral retina becomes more important for spatial referencing. Moreover studies have shown that individuals with greater visual field dependence are also more sensitive to peripheral visual cues such as motion and orientation.^{11,56,63,64} It would be interesting to examine visual field dependence in age-related visual pathologies that impact the peripheral retina, such as glaucoma, to better understand the mediating effect of peripheral cues on the increased visual field dependence we observed in our population of older adults with CFL.

Limitations

A limitation of our study is the inherent heterogeneity of the CFL population represented in our sample. We therefore chose to separate our visually impaired participants in terms of the two factors guiding our study: whether disease onset was in young or older age and whether vision loss was ever-present (CFL) or limited to a single eye or lower contrast viewing (mCFL). Further, where possible, we examined the effects of visual deficits as a continuum (Fig. 5), finding that better contrast sensitivity was associated with reduced visual field dependence across our entire older adult population. One may argue that the spatial aberrations associated with CFL⁶⁵ may have contributed to errors in orientation judgment in this population. However, these errors should have affected participants with CFL biases in both the conditions with and without a visual reference. Thus, visual field dependence differences are unlikely due to visual distortions caused by CFL.

Finally, we should note that individuals with CFL tend to limit their physical activities due to their visual impairment⁶⁶ and concerns about falling.^{67,68} Although we did not obtain objective measures of physical activity or standardized self-reports, it is possible that a more sedentary lifestyle in those with binocular CFL led to higher levels of visual field

dependence compared to their visually healthy peers. Future work should consider how physical fitness may interact with visual field dependence in older adults with CFL.

CONCLUSIONS

Visual field dependence is ultimately a matter of sensory integration for the perception of one's environment and control of their own motion within it. In older age, overrelying on visual cues can be problematic because behaviors associated with visual field dependence, such as reduced adaptation capacity⁶⁹ and fall propensity,^{22,64} cannot be compensated for appropriately given normal aging deficits.^{6,12,37} The addition of poor vision may make visual field dependence a riskier mode of spatial referencing in older adults with CFL.

We found an increase in visual field dependence in our older participants with binocular CFL compared to age-matched controls and a similar level for those with monocular or non-overlapping binocular CFL. The next step would be to examine how this finding translates to more ecological situations, such as balance and locomotion, and to understand whether such persisting visual field dependence is maladaptive. Indeed, it is worth examining the extent and rigidity (does one still rely on visual cues when these are manipulated to become explicitly more unreliable?) of visual field dependence in individuals with CFL to better understand the care and potential rehabilitative measures they will need. Additionally, previous research suggests that increased visual field dependence is associated with fixational instability,⁴ a known oculomotor consequence of CFL.⁷⁰ Hence, it would be an interesting next step to examine this relationship in CFL.

Finally, visual field dependence could be considered when aiming to provide rehabilitation and mobility solutions to older adults with CFL, as has been previously suggested for visually healthy older adults.⁴³ Indeed, some individuals may benefit more from sensorimotor training to reduce their visual field dependence and boost reliance on body-based senses rather than use aids that may contribute to visual field perturbation during locomotion, such as telescopic lenses⁷¹ or augmented reality-based devices.⁷² For example, research has shown that exposure to dynamic visual stimuli can reduce visual field dependence (in terms of both perception and postural control) in healthy young⁷³ and older adults.² Encouraging rehabilitative potential has also been shown through training in environments that create sensorimotor conflicts in healthy older adults,⁷⁴ as well as those with CFL.³⁶ Aging and central vision loss are both heterogeneous processes, and indeed there is individual variability in our own dataset. Studying the degree of an individual's visual field dependence relative to sensory and motor function can allow for better-suited training and treatment of older adults losing their central vision and consequently could improve their autonomy and quality of life.

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