A paradigm for characterizing motion misperception in people with typical vision and low vision

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SIGNIFICANCE: Motion perception is an essential part of visual function. Understanding how people with low vision perceive motion can therefore inform rehabilitation strategies and assistive technology. Our study introduces the notion of Bayesian biases in motion perception and suggests that some people with low vision are susceptible to these systematic misperceptions.

PURPOSE: We aimed to develop a paradigm that can efficiently characterize motion percepts in people with low vision and compare their responses with well-known misperceptions made by people with typical vision when targets are hard to see.

METHODS: We recruited a small cohort of individuals with reduced acuity and contrast sensitivity (n = 5) as well as a comparison cohort with typical vision (n = 5) to complete a psychophysical study. Study participants were asked to judge the motion direction of a tilted rhombus that was either high or low contrast. In a series of trials, the rhombus oscillated vertically, horizontally, or diagonally. Participants indicated the perceived motion direction using a number wheel with 12 possible directions, and statistical tests were used to examine response biases.

RESULTS: All participants with typical vision showed systematic misperceptions well predicted by a Bayesian inference model. Specifically, their perception of vertical or horizontal motion was biased toward directions orthogonal to the long axis of the rhombus. They had larger biases for hard-to-see (low contrast) stimuli. Two participants with low vision had a similar bias, but with no difference between high- and low-contrast stimuli. The other participants with low vision were unbiased in their percepts or biased in the opposite direction.

CONCLUSIONS: Our results suggest that some people with low vision may misperceive motion in a systematic way similar to people with typical vision. However, we observed large individual differences. Future work will aim to uncover reasons for such differences and identify aspects of vision that predict susceptibility.

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Motion perception is vital to our ability to perform many activities of daily living. Safe orientation and mobility, for example, require people to estimate their own self-motion and determine if any obstacles are moving into their path. Previous research has shown that diverse forms of low vision can cause reductions in visual motion sensitivity across the visual field, affecting an individual's safety and independence during mobility.[1–8] Reductions in visual motion sensitivity, by definition, result in an increase in random errors in the detection or discrimination of moving targets. However, people with low vision may also experience *systematic* misperceptions of the speed and direction of motion when targets are hard to see. Such misperceptions associated with low vision have not been investigated. Here, we describe a well-known example of systematic motion misperceptions in people with typical vision, introduce an experimental paradigm for quantifying these misperceptions in people with both typical vision and low vision, and present a preliminary study of these motion misperceptions in a small cohort of individuals.

Psychophysical research has shown that people with typical vision are susceptible to systematic misperceptions of the motion of hard-to-see patterns and shapes—that is, their errors are not random.[9–16] For example, previous work has consistently found that people with typical vision perceive gratings or dots as moving more slowly when these stimuli are low visibility (e.g., low contrast) (Fig. 1A).[9,15] It has been proposed that this speed misperception is the consequence of a probabilistic inference process that the human visual system uses to estimate motion in the world.[16] The hypothesis goes as follows: when moving stimuli are hard to see (i.e., visual information is less reliable), the visual system relies more on a prior expectation that objects in the environment tend to move slowly (or not at all), leading to a bias for perceiving slower speeds of motion. The reliance on prior expectations can be mathematically formalized using the Bayesian inference framework, in which noisy sensory information is optimally combined with prior expectations.[17] At the same time, non-Bayesian accounts for slow-speed biases have also been proposed, which we will return to in the Discussion.[18–20] Regardless of the underlying cause, previous work suggests that these motion misperceptions have complex effects on the performance of people with typical vision during real-world tasks, for example, when driving through fog[21,22] or estimating motion trajectories of projectiles.[23,24]

We aimed to examine whether the motion misperceptions experienced by people with typical vision are also experienced by people with low vision. Measuring biases in perceived speed directly, however, is challenging. Previous experiments measuring

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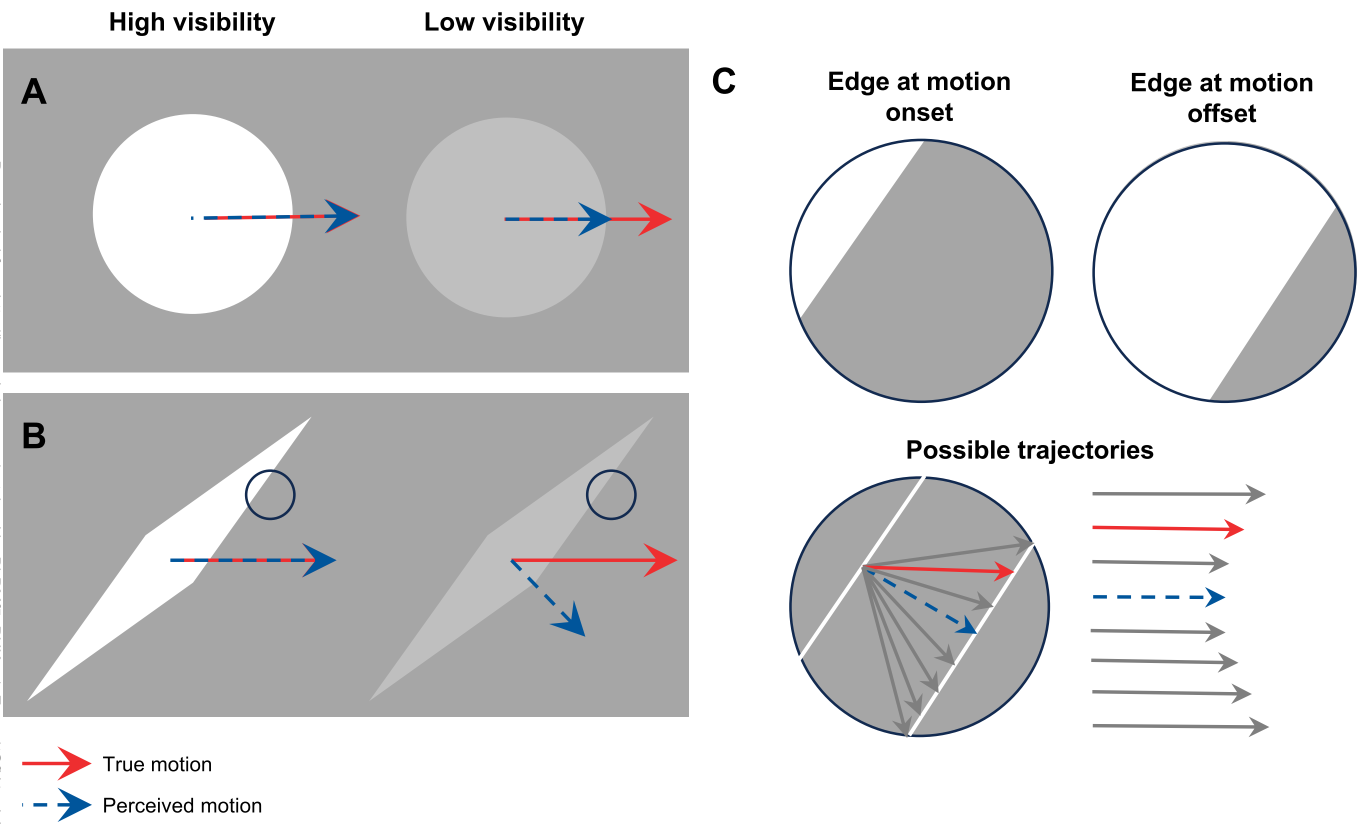

FIGURE 1. When moving targets are hard to see, people with typical vision make systematic errors in judging their speed and direction of motion. (A) When people are presented with moving gratings or dots, they tend to see patterns with lower visibility as moving more slowly. For example, if people view a high- and low-contrast dot moving rightward at the same speed (solid red arrows), they may misperceive the lower contrast dot to move more slowly (dashed blue arrows). (B) This slow-speed bias can affect percepts of motion direction also. For example, a low-contrast rhombus that moves rightward may be perceived instead as moving slowly in a diagonal direction orthogonal to its major axis. This motion bias likely occurs because motion direction is ambiguous within local regions, or apertures, along the edges of the shape (black circles). (**C**) People are biased to perceive the direction associated with the slowest speed within these apertures. The illustration shows that the motion of the edge within the aperture is ambiguous (arrows indicate possible motion directions). The dashed blue arrow represents the direction associated with the slowest speed because the edge traverses the shortest distance within a fixed length of time.

slow-speed biases often involved asking participants to make relative speed judgments between pairs of high-visibility and low-visibility stimuli.[9,12] Such experiments require many trials and are not informative about the overall accuracy of motion percepts—they can only inform as to whether speed perception differs between stimuli, not whether it is biased away from ground truth. Asking participants to report the absolute speed of individual moving targets, which avoids these issues, is viable in principle but in practice requires highly trained expert observers,[25] as most people find it challenging to report absolute perceived speed in physical units (e.g., meters/second). Furthermore, absolute speed judgments are noticeably nonlinear,[26] and it is easy to confound speed with distance in such experiments.[27] Thus, direct measurements of perceived speed are not ideal for assessing perceptual biases in low-vision populations.

On the other hand, judgments of motion direction are more intuitive for naive observers. Conveniently, there exists a robust visual illusion of perceived motion direction that is associated with slow-speed biases, and we leveraged this illusion to measure motion misperception. In this illusion, translating a low-contrast rhombus shape horizontally or vertically makes people consistently perceive the motion to be orthogonal to the major axis (i.e., the longer axis), even when it is not (Fig. 1B, Supplemental Video 1, available at http://links.lww.com/OPX/A734).[16] This motion direction illusion occurs because of how the slow-speed bias interacts with the well-known motion aperture problem. Psychophysical and neurophysiological studies suggest that the visual system estimates the motion direction of an object by first estimating motion within local regions, or "apertures," at the object's edges, and then integrating these estimates (Fig. 1B, small circle).[28–33] However, within an aperture, local edge motion direction is inherently ambiguous—that is, the same stimulus can be generated by an infinite number of different speeds and directions (Fig. 1C).[34] Nonetheless, when people with typical vision view contours moving through an isotropic aperture, they consistently perceive such edges to be moving in the direction orthogonal to the local edge orientation.[35] This percept is consistent with a slow-speed bias—that is, the local direction associated with the slowest speed is indeed the direction orthogonal to the edge (Fig. 1C, shortest arrow length indicated with a blue dashed line). When viewing whole objects with contours of different orientations, this local bias in estimated direction is typically overridden because the global shape now provides constraints that can disambiguate local motion. However, the motion direction bias can persist when an object is hard to see because the visual cues that inform the true object direction and speed become less reliable. Thus, assessments of motion direction biases provide a promising avenue for characterizing motion misperception in both people with typical vision and low vision.

It is essential to understand whether speed and direction biases affect the motion perception of people with low vision because systematic motion misperceptions can interfere with key visual functions like predicting potential collisions. On the one hand, if people with low vision are subject to the same biases as typically sighted individuals, we would expect them to systematically misperceive motion for targets that are hard to see. On the other hand, living with low vision, particularly congenitally, likely changes the way that people develop expectations about the visual world. Thus, an alternative strategy might be to downweight any prior assumptions of slow speeds, resulting in reduced motion misperceptions relative to people with typical vision.

Here, we present an experimental paradigm and preliminary data examining whether and how slow-speed biases affect the motion perception of people with low vision. We adopted a variation of the moving rhombus paradigm described previously and modified it for efficiently collecting controlled measurements of perceived and misperceived motion direction. Using this paradigm, we characterized motion direction judgments in a small cohort of people with low vision and a comparison group of participants with typical vision. Recruitment of people with low vision was targeted to individuals with reduced contrast sensitivity, while preserving enough visual acuity to perform the experimental task. Although the participants with typical vision largely conformed to expectations from previous work, the participants with low vision had more varied response patterns that shed light on the diverse ways that visual uncertainty affects perception. Ultimately, we hope that these results can help broaden our understanding of how low vision affects motion perception and guide the development of innovative assistive technologies and rehabilitation strategies that support visually demanding tasks. In turn, these insights can also help us better understand the breadth and validity of Bayesian inference frameworks for characterizing visual perception in people with diverse lived experiences.

METHODS

Participants

Five participants with low vision were recruited from the Low Vision Clinic at the Meredith Morgan Eye Center at the University of California, Berkeley. Eligible participants were contacted on the basis of *International Classification of Diseases, Tenth Revision* codes associated with mild to moderate reductions in contrast sensitivity, and no exclusion criteria were used except for the ability to perform the task. Recruitment yielded three participants with albinism, another with albinism and glaucoma, and one with Stargardt disease. For a comparison group, five additional participants with typical vision were recruited. The criteria for typical vision were best-corrected binocular visual acuity of 0 logMAR or better and no known ocular pathology. One participant initially recruited with typical vision was excluded because we learned that they wore monovision correction for presbyopia. Table 1 provides individual information about each participant. Visual acuity was measured with an optotype (letter) chart at 6 m for participants with typical vision and at variable distances for participants with low vision, depending on their viewing ability (see Table 1 caption). Contrast sensitivity was measured using a Mars Contrast Sensitivity Test at near distance (50 cm). All participants with low vision except for one (OA) had impaired contrast sensitivity on this test. Nystagmus was not characterized—albinism is generally associated with a horizontal nystagmus; however, the strength and waveform can vary depending on gaze direction.[36,37] This research was reviewed by an independent ethical review board and conforms with the principles and applicable guidelines for the protection of human subjects in biomedical research. All participants gave informed consent and were compensated for their time.

Stimulus and task

Stimulus

Participants were presented with an oscillating rhombus and asked to judge its motion direction. All stimuli were presented on an LCD monitor with 10-bit luminance precision and a refresh rate of 120 Hz (ViewPixx 3D). Participants viewed the monitor binocularly from a distance of 40 cm in a dark room. The rhombus shape was always 6° tall and 1° wide. There were four possible true motion directions, which were pseudorandomized across trials: up-down, left-right, diagonal from upper left to lower right, and diagonal from upper right to lower left. Across trials, we also varied the rhombus orientation and speed to cover a range of visual appearances and motions (see next section). To examine the effect of

TABLE 1. Participant demographics and vision information

P #	Age (y)	Gender	Etiology	logMAR acuity (OD/OS/OU)	Log contrast sensitivity (OD/OS/OU)	Duration of impairment	Rhombus low contrast (%)
Low vision group							
OA	56	M	Ocular albinism	0.64/0.74/0.64	1.80/1.76/1.80	Since birth	2.02
OAG	32	M	Ocular albinism, glaucoma	1.34/1.46/1.40	1.04/0.72/1.12	OA since birth, G past 14 y	10.48
OC1	51	M	Oculocutaneous albinism	1.25/1.25/1.25	1.36/1.40/1.40	Since birth	4.54
OC2	40	F	Oculocutaneous albinism	0.42/0.52/0.42	1.68/1.64/1.64	Since birth	1.92
SD	43	F	Stargardt disease*	0.64/0.74/0.62	1.00/0.96/1.28	Past 2 y	1.70
Typical vision group							
T1	23	M	—	−0.12/−0.10/−0.12	1.68/1.80/1.84	—	1.27
T2	32	M	—	−0.10/−0.04/−0.08	1.80/1.52/1.76	—	0.11
T3	23	F	—	−0.04/−0.10/−0.08	1.76/1.47/1.80	—	0.74
T4	29	F	—	−0.10/−0.10/−0.10	1.80/1.68/1.80	—	0.95
T5	24	M	—	−0.10/−0.10/−0.10	1.80/1.80/1.84	—	1.59

Each row provides the age in years, gender (M = male, F = female), low vision etiology, visual acuity in units of the logarithm of the minimum angle of resolution (logMAR), contrast sensitivity (log units), and duration of impairment for each study participant. Acuity was measured at 6 m for all participants except OAG (1.2 m), OC1 (1.7 m), and OC2 (3 m), who could not see the chart at 6 m. The rhombus contrast threshold is reported in Weber units and was measured as described in the methods. *Participant SD has late-onset Stargardt disease, with visual changes that started 4 years ago and a diagnosis of low vision 2 years ago. G = glaucoma; OA = ocular albinism; OC = oculocutaneous albinism; SD = Stargardt disease.

visibility on motion misperceptions, for each participant the rhombus was presented at two different contrast levels: one at high-contrast and another at a low-contrast level customized so that the stimulus was just barely visible. For the high-contrast condition, the rhombus was filled with the maximum white level of the display (92 cd/m^2) and presented against a gray background (29 cd/m^2), resulting in 217% Weber contrast of the rhombus on the display. The rhombus luminance for the low-contrast condition was determined for each participant via a separate psychophysical procedure (see next section) that preceded the main task.

Main task

For the main task, on each trial, a white dot first cued the participants to look at the center of the screen. After 1 second, the dot was replaced by the oscillating rhombus stimulus. On a given trial, the appearance of the rhombus varied in several ways. The rhombus could be tilted 45° clockwise (as illustrated in Fig. 1B) or 45° counterclockwise, and it moved at one of two possible speeds: 4°/s or 1°/s. The rhombus moved at a constant speed and changed direction at a rate of 2 Hz, traversing 0.5 visual degrees for the slow speed and 2 degrees for the fast speed. After the trial was completed, a response screen appeared, showing a number wheel with 12 spokes indicating possible motion axes in steps of 15°. Participants verbally called out the number of the spoke that corresponded to the direction they saw the rhombus moving (e.g., one for vertical up/down motion, two for tilted 15° from vertical, three for tilted 30° from vertical, etc.), which was recorded via keyboard by the experimenter. To aid visibility, some participants with low vision were also separately provided with the number wheel on a tablet with larger font. Participants were instructed to select a motion direction as best as they could, but they were also given the option of selecting "no motion," for example, if they failed to detect the rhombus or failed to detect any motion on a given trial. All participants had 12 practice trials to get familiar with the task before data collection. Data were collected for a total of 192 trials (four motion directions × two contrasts × two rhombus orientations × two speeds × six repeats) presented in pseudorandom order.

Contrast adjustment task

Before the main task, an auxiliary task was conducted to determine the rhombus luminance in the low-contrast condition. In the auxiliary task, we used the method of adjustment to allow the participants to find the luminance at which the rhombus was barely detectable. During the adjustment phase, a rhombus moving at 1°/s horizontally was shown, and participants decreased its contrast to be as low as possible while still being visible. This procedure was repeated five times, and the average of the five adjusted contrasts was used as the low contrast value for each participant. The average Weber contrast setting of the rhombus for each participant is reported in the final column of Table 1. These settings do not necessarily correlate with results from the Mars Contrast Sensitivity Test because they reflect people's subjective assessments of visibility of a moving rhombus stimulus specific to our task. Despite the variation, contrast settings tended to be higher in the participants with low vision, consistent with their lower clinical contrast sensitivity.

Analysis

If people are unbiased in their perception of motion direction, we would expect any errors to be equally distributed in directions clockwise and counterclockwise of the true direction of motion. However, if people have a directional bias, we expect them to make systematic errors contingent on the orientation of the rhombus. In accordance with previous work and our demonstration in Supplementary Video 1, available at http://links.lww.com/OPX/A734, we predicted perceived motion to be drawn toward the direction associated with the slowest movement of local edges, that is, diagonal motion orthogonal to the major axis (Fig. 1C). This pattern should result in biased errors on trials when the true rhombus movement was horizontal or vertical, but unbiased errors when the true movement was already diagonal. A detailed computational explanation of this predicted bias is presented in Weiss et al.[16]

We analyzed each participant's data separately because we wanted to examine potential individual differences. To examine whether participants' responses showed evidence of the predicted bias, we first converted their number wheel responses into angles increasing in the counterclockwise direction, with 0/180° indicating a rightward/leftward response (see polar plot labels in Fig. 2). Error on a given trial was defined as the minimum circular distance in degrees between the true motion direction of the stimulus and the responded direction. Clockwise errors were positive, and counterclockwise errors were negative.

Because we were not explicitly interested in differences between responses to the two rhombus orientations and speeds, we combined participants' responses across these factors. Specifically, we mirror-reflected responses from trials in which the rhombus was oriented 45° counterclockwise about the horizontal axis. Thus, regardless of the original rhombus orientation, when the true motion direction was horizontal, clockwise (positive) errors always indicated a bias toward the Bayesian prediction (see Fig. 2A, in which the black line indicates true motion direction and the dashed orange line represents the predicted Bayesian bias). When the true motion direction was vertical, errors indicating a bias toward the Bayesian prediction were always counterclockwise (negative) errors (Fig. 2C). We had no hypotheses about differences in direction biases between speeds, and as visual examination of the different speeds suggested no differences, we also combined across the speeds.

In addition to separately examining the errors for horizontal and vertical motion, we wanted to produce a combined bias estimate that included both horizontal and vertical motion trials. Because the Bayesian prediction in these two conditions simply differed in sign, to produce an overall measure of Bayesian bias, we just sign-reversed the error values from the vertical motion trials and then combined them with the error values from the horizontal motion trials. For trials in which the true motion direction was diagonal, there was no predicted bias; however, we combined the errors according to the following rules: positive errors indicated response biases toward vertical motion, and negative errors indicated response biases toward horizontal motion.

We used *t* tests to assess whether the errors were, on average, significantly different from zero (no bias) in both the high- and low-contrast conditions, as well as whether there were significant differences in the magnitude of bias between the high- and low-contrast conditions. We applied Bonferroni correction to all p values to correct for the three statistical tests within subjects, resulting in a significance threshold of $p<0.0167$. Effect sizes (Cohen's d) are also reported for each comparison.

RESULTS

As expected from previous reports, participants with typical vision made systematic errors in their judgment of motion direction. Fig. 2A shows polar histograms of the responses of each of these participants when the rhombus moved horizontally. The green and orange wedges represent the frequency of the responses (aggregated into angular bins of 15°) when the rhombus was high and low contrast, respectively. These responses tended to be biased away from the true motion (solid black line) and toward the Bayesian prediction (dashed orange line), particularly when viewing the low-contrast

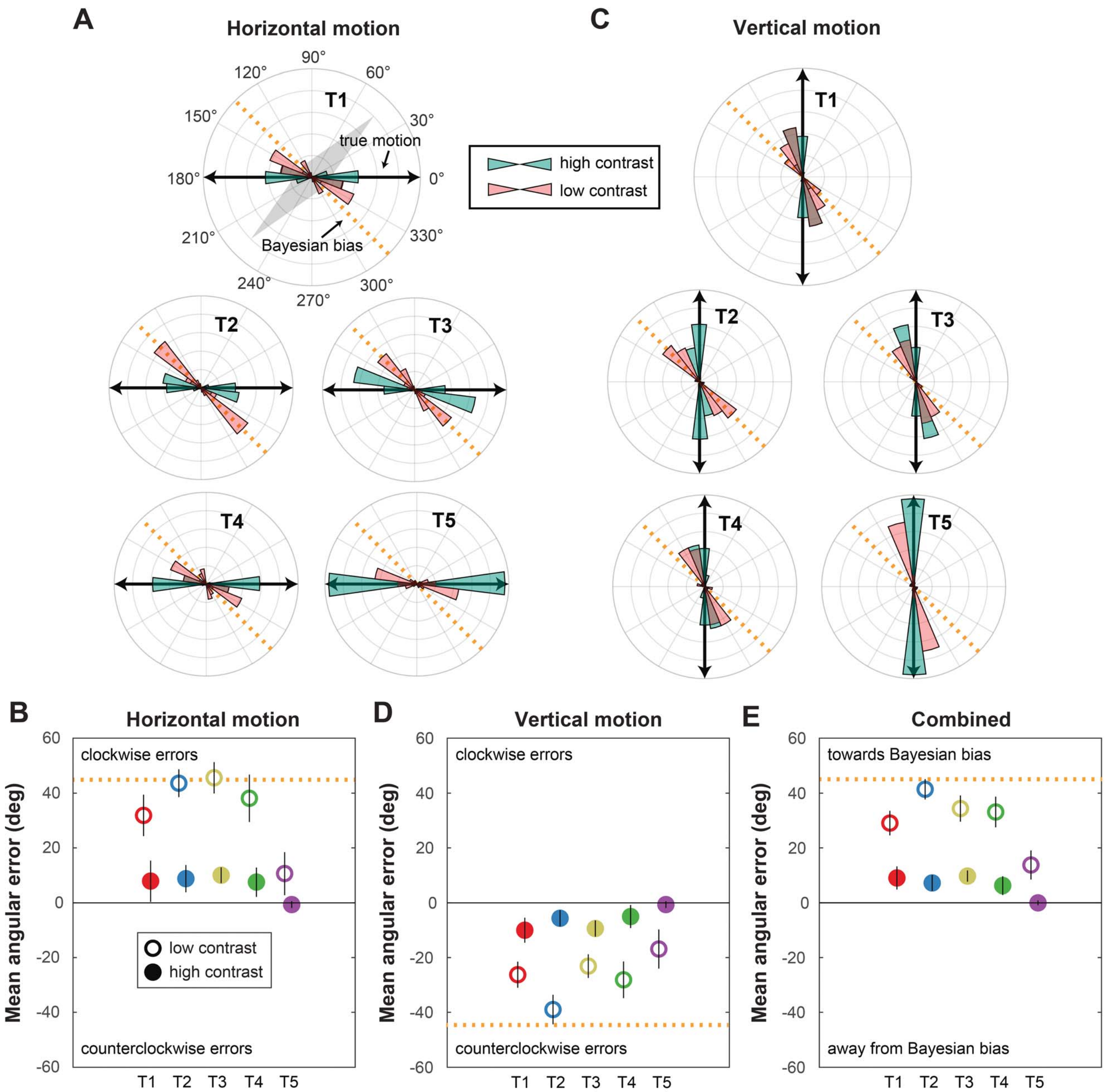

FIGURE 2. Motion direction responses and error analysis for participants with typical vision on trials when the rhombus moved in a cardinal direction: horizontally (A, B) or vertically (C, D). (A) For trials in which the stimulus moved horizontally (black line labeled "true motion"), each polar plot shows a histogram of the responses for one participant. The shaded gray region illustrates the rhombus in the clockwise orientation. For clarity, annotations are included in the first plot only. Histogram bins are "bow tie" shaped, reflecting the frequency of motion responses along a given axis. In polar coordinates, right/left motion corresponds to the 0/180° axis, and up/down motion corresponds to the 90/270° axis. The dashed orange line indicates the predicted direction associated with the Bayesian slow-speed bias, corresponding to the direction orthogonal to the major axis of the rhombus (shaded gray region in top plot). Each polar histogram has a radius of 0.5 in units of probability. (B) Mean angular error for each participant on trials when the rhombus moved horizontally is shown, for both the low- and high-contrast stimuli. Averages were computed for all trials in which the participant reported seeing motion. Error bars represent 95% confidence intervals. Each participant is coded in a different color. The horizontal lines indicate the errors associated with responding with the true motion (solid black line) or responding with the exact Bayesian bias (dashed orange line). (C) Histograms of motion direction responses for trials in which the stimulus moved vertically are plotted, for the same participants as in (A). (D) Mean angular error and 95% confidence intervals are plotted for each participant on trials when the rhombus moved vertically, in the same manner as (B). (E) Mean combined angular error and 95% confidence interval are shown for each participant on all trials, including both horizontal and vertical motion. For this plot, the signs of the errors for the vertical motion trials were reversed. As such, positive values indicate errors in the direction of the Bayesian bias, and negative values indicate errors in the opposite direction.

stimulus. That is, people tended to report that the rhombus moved in a direction orthogonal to the major axis, even when it did not. As predicted, when the true motion was horizontal, this response bias produced an excess of errors in the clockwise (positive) direction from the true motion. Fig. 2B shows the mean error and 95% confidence interval for each participant on the horizontal motion trials, which was clockwise for all participants except participant T5 in the high-contrast condition, for which the mean error was 0°. When the rhombus moved vertically, the responses were also consistent with the predicted Bayesian bias (Fig. 2C). In this case, the response bias produces an excess of errors in the counterclockwise (negative) direction (Fig. 2D).

As described in Methods, we can combine across these two conditions by reversing the sign of the vertical motion trial errors to produce an overall estimate of each participant's bias, plotted in Fig. 2E. We conducted statistical analyses on these overall bias estimates (Table 2), which showed that they were significantly greater than 0 for all participants in the low-contrast condition and for all but one participant (T5) in the high-contrast condition. We would expect the bias to be stronger when the stimulus is harder to see, and this expectation was also supported by the statistical analysis and the effect sizes: the biases tended to be significantly different and notably larger in the low-contrast condition (larger Cohen's *d* values) as compared with the high-contrast condition. Reports of "no motion" were relatively rare in this group, averaging less than 10% across all conditions for each participant.

Participants with low vision reported more varied percepts of motion direction. Fig. 3 shows the same polar response histograms for these participants' responses, along with summaries of their mean errors. When the true motion was horizontal, most participants with low vision tended to make clockwise errors consistent with the Bayesian bias prediction. However, the error magnitudes were highly variable, and contrary to the prediction, the errors did not differ substantially for the high- and low-contrast stimuli (Figs. 3A, B). When the motion was vertical, only two participants (SD and OC2) tended to make errors consistent with a Bayesian bias (Figs. 3C, D). Although differences in sensitivity to horizontal and vertical motion have been previously identified in individuals with nystagmus, here we proceed with combining these directions to examine our specific hypothesis, which posits that Bayesian biases can account for misperceptions across both directions.[38–40] We will return to the potential role of nystagmus in motion misperception in the Discussion.

Combining across horizontal and vertical motion conditions as in the previous analysis, only two participants (SD and OC2) had biases significantly greater than zero (Fig. 3E, Table 2). Notably, however, these two participants had no significant differences between the high- and low-contrast stimuli, and the effect sizes associated with high and low contrast were also similar. Thus, although participants with low vision made errors, their misperceptions were only systematic and consistent with the predicted Bayesian bias in some cases.

We also noted that there were individual differences in the percentage of trials in which participants reported seeing no motion. Participants OC1 and OC2 selected this response with the highest frequencies (25.0% of 21.8% of trials, respectively), whereas OA reported fewer no motion trials (8.3%). Participants OAG and SD never used this response option. When OC1 and OC2 reported no motion, it was always on trials in which the stimulus speed was slow. However, the frequency of selecting the no-motion response did not otherwise bear a clear relationship to the motion direction misperceptions.

In addition to our main analyses, we also examined the pattern of errors when the true rhombus motion was diagonal. These trials served to ensure that participants experienced a range of different true motion directions throughout the experiment in addition to acting as control conditions because we did not expect to observe systematic biases. In Fig. 4A, we show the average responses across all participants with typical vision for the trials in which the ground-truth motion was orthogonal to the long axis. In this condition, both the true motion and the Bayesian bias are the same (solid black line and orange dashed line). Interestingly, the participants with typical vision tended to have a slight bias to perceive the diagonal motion as more vertical. Fig. 4B shows the average biases collapsed across all diagonal motion trials, which makes this trend clearer. Most, but not all, participants had statistically significant vertical biases

TABLE 2. Results of *t* tests for each participant's response bias on trials when the rhombus moved in a cardinal direction (horizontally or vertically)

	Low-contrast bias				High-contrast bias				High versus low contrast			
						Typical vision						
P #	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*
T1	**12.66**	**47**	**<0.001**	**1.8**	**4.18**	**44**	**<0.001**	**0.61**	**−6.36**	**91**	**<0.001**	**1.3**
T2	**21.81**	**41**	**<0.001**	**3.3**	**4.85**	**47**	**<0.001**	**0.69**	**−14.39**	**88**	**<0.001**	**3.0**
T3	**14.06**	**47**	**<0.001**	**2.0**	**9.26**	**47**	**<0.001**	**1.3**	**−9.28**	**94**	**<0.001**	**1.9**
T4	**11.59**	**47**	**<0.001**	**1.6**	**3.63**	**47**	**<0.001**	**0.52**	**−8.06**	**94**	**<0.001**	**1.6**
T5	**5.07**	**47**	**<0.001**	**0.72**	—	—	—	—	**−5.01**	**94**	**<0.001**	**1.0**
						Low vision						
P #	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*
OA	−2.19	45	0.033	0.32	−1.46	39	0.15	0.23	0.857	84	0.39	0.19
OAG	0.71	47	0.479	0.10	0.22	47	0.83	0.03	−0.395	94	0.69	0.08
OC1	−1.38	36	0.176	0.22	−0.84	35	0.41	0.14	0.431	71	0.67	0.10
OC2	**3.10**	**36**	**0.004**	**0.55**	**4.07**	**39**	**<0.001**	**0.63**	0.027	75	0.98	0.01
SD	**3.12**	**47**	**0.003**	**0.44**	**4.27**	**47**	**<0.001**	**0.61**	0.442	94	0.66	0.09

Each column indicates the test statistic value (*t*), degrees of freedom (*df*), p value, or effect size (*Cd*) for each participant and each test. Three *t* tests were run for each participant, with a null hypothesis of zero bias for low contrast, zero bias for high contrast, and zero difference in bias between the two conditions. Degrees of freedom differ across participants because any trials with a no-motion response are excluded. Statistically significant results are bolded, with a Bonferroni-corrected threshold of $p<0.0167$. Cd = Cohen's *d*.

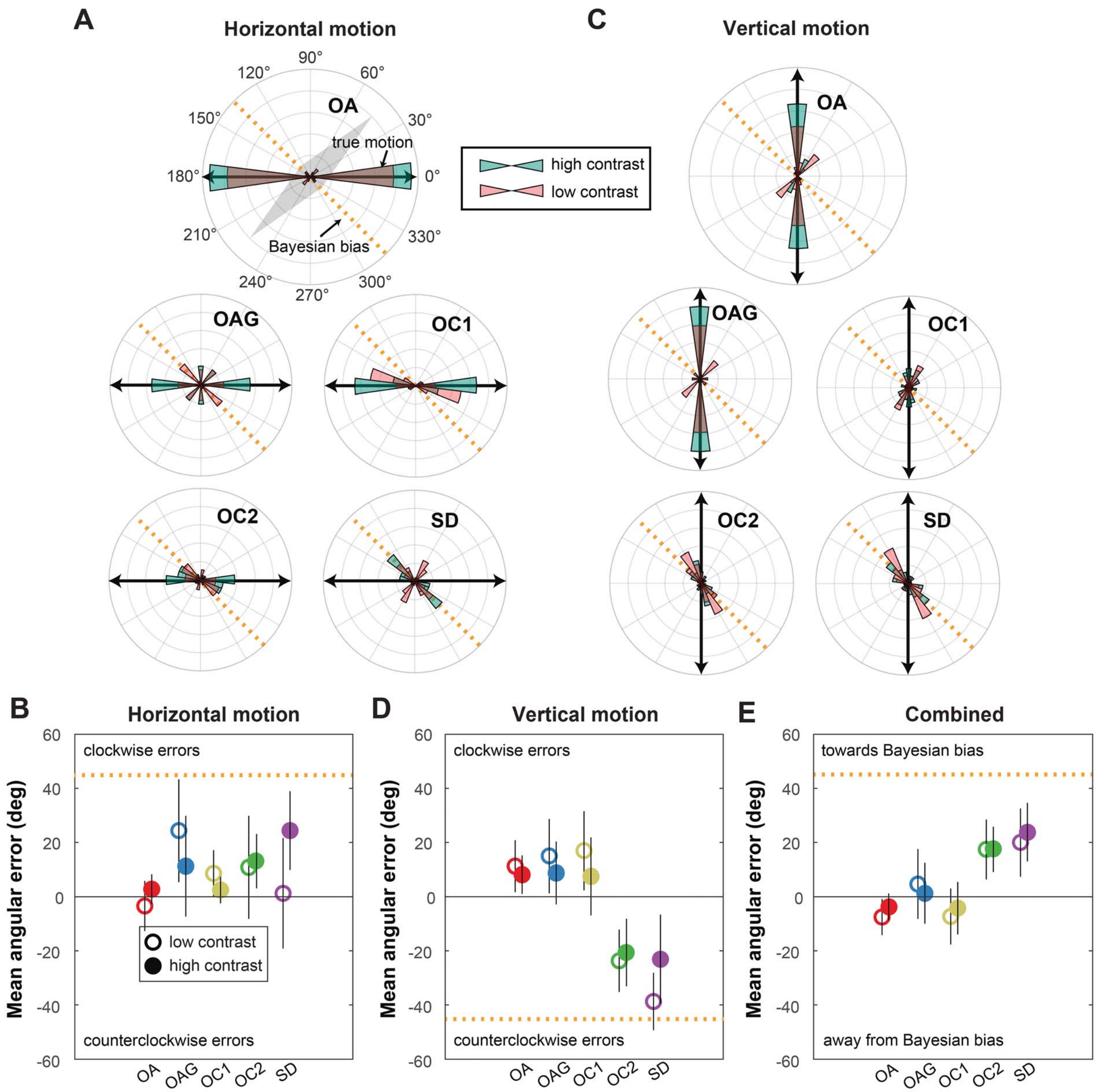

FIGURE 3. Motion direction responses and error analysis for participants with low vision on trials when the rhombus moved in a cardinal direction: horizontally (A, B) or vertically (C, D). (A) For trials in which the stimulus moved horizontally (black line labeled "true motion"), each polar plot shows a histogram of the motion direction responses for one participant. The shaded gray region illustrates the rhombus in the clockwise orientation. For clarity, annotations are included in the first plot only. Histogram bins are "bow tie" shaped, reflecting the frequency of motion responses along a given axis. In polar coordinates, right/left motion corresponds to the 0/180° axis, and up/down motion corresponds to the 90/270° axis. The dashed orange line indicates the predicted direction associated with the Bayesian slow-speed bias, corresponding to the direction orthogonal to the major axis of the rhombus (shaded gray region in top plot). Each polar histogram has a radius of 0.5 in units of probability. (B) Mean angular error for each participant on trials when the rhombus moved horizontally is shown, for both the low- and high-contrast stimuli. Averages were computed for all trials in which the participant reported seeing motion. Error bars represent 95% confidence intervals. Each participant is coded in a different color. The horizontal lines indicate the errors associated with responding with the true motion (solid black line) or responding with the exact Bayesian bias (dashed orange line). (C) Histograms of motion direction responses for trials in which the stimulus moved vertically are plotted, for the same participants as in (A). (D) Mean angular error and 95% confidence intervals are plotted for each participant on trials when the rhombus moved vertically, in the same manner as (B). (E) Mean combined angular error and 95% confidence interval are shown for each participant on all trials, including both horizontal and vertical motion. For this plot, the signs of the errors for the vertical motion trials were reversed. As such, positive values indicate errors in the direction of the Bayesian bias, and negative values indicate errors in the opposite direction.

TABLE 3. Results of *t* tests for each participant on trials when the rhombus moved diagonally

	Low-contrast bias				High-contrast bias				High versus low contrast			
					Typical vision							
P #	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*
T1	1.59	47	0.12	0.23	**3.29**	**47**	**0.002**	**0.47**	0.826	94	0.41	1.8
T2	1.26	34	0.22	0.21	1.85	47	0.07	0.26	−0.827	81	0.41	3.0
T3	**8.30**	**38**	**<0.001**	**1.3**	**13.3**	**46**	**<0.001**	**1.9**	0.005	84	0.996	1.6
T4	**3.68**	**46**	**<0.001**	**0.53**	**3.19**	**47**	**0.003**	**0.45**	−0.198	93	0.84	1.7
T5	**5.31**	**47**	**<0.001**	**0.75**	**7.47**	**47**	**<0.001**	**1.1**	0.681	94	0.50	0.18
					Low vision							
P #	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*	*t*	*df*	p	*Cd*
OA	0.274	41	0.79	0.04	**4.56**	**47**	**<0.001**	**0.65**	2.31	88	0.02	0.92
OAG	1.96	47	0.056	0.28	0.778	47	0.44	0.11	−0.891	94	0.38	0.02
OC1	−0.649	34	0.52	0.11	−1.44	34	0.16	0.24	−0.346	68	0.73	0.11
OC2	−1.17	32	0.25	0.2	1.1	41	0.28	0.17	1.59	73	0.12	0.39
SD	−0.767	47	0.45	0.11	2.22	47	0.031	0.32	1.69	94	0.094	0.34

Each column indicates the test statistic value (*t*), degrees of freedom (*df*), p value, or effect size (*Cd*) for each participant and each test. Three *t* tests were run for each participant, with a null hypothesis of zero bias for low contrast, zero bias for high contrast, and zero difference in bias between the two conditions. Statistically significant results are bolded, with a Bonferroni-corrected threshold of $p<0.0167$. Cd = Cohen's *d*.

(Table 3). For participants with low vision, the direction of these biases differed across individuals, and only one was statistically significant (Figs. 4C, D; Table 3). We did not find a contrast-dependent effect in either group, consistent with the idea that these biases are not related to visual uncertainty. These small additional biases highlight the fact that people may have varied expectations about motion that influence their interpretations of stimuli like those used in our experiment. For example, biases toward vertical motion may reflect anisotropies in the representation of the visual field or expectations about how objects tend to move in the world due to gravity.[41–43]

DISCUSSION

People rely on motion perception for a variety of daily tasks, so motion misperceptions have the potential to negatively impact quality of life, safety, and independence. Previous work on motion perception in low vision has largely focused on characterizing how low vision limits motion sensitivity, which involves examining random rather than systematic errors.[1–6] Thus, little is known about the association between low vision and systematic misperceptions of motion speed and direction. Understanding systematic misperceptions is of particular interest for developing assistive technologies and rehabilitation strategies because these errors may be predictable across different scenarios.

In this work, we developed a paradigm to investigate motion misperceptions that uses a simple stimulus to reveal perceptual biases in both typical and low-vision populations. Our paradigm leverages the tendency for people to underestimate the speed of objects that are hard to see, which is well explained by a Bayesian inference framework in which people have a prior expectation that objects in the world tend to be either stationary or slow. Our results suggest a highly individualized influence of bias on motion misperception with low vision, as opposed to the stereotyped biases we found in participants with typical vision. Whereas some of the participants with low vision in this study had rather strong biases consistent with the Bayesian model, others did not. Here, we discuss some potential interpretations of these findings, key caveats, and implications for visual function and assistive technology.

Most of our research participants (four out of five) with low vision had forms of albinism, which is associated with variable levels of visual impairment because it affects the development of the visual system, the scattering of light within the eye, and also often includes abnormal eye movements in the form of nystagmus (primarily horizontal). Studies of motion detection and discrimination in individuals with congenital nystagmus, including some with albinism, suggest an overall reduction in motion sensitivity that is strongest for horizontal motion (parallel the dominant nystagmus direction).[39,40] The large random errors observed in our study (i.e., the large 95% confidence intervals in Fig. 3) may reflect an overall reduction in motion sensitivity, which makes it more challenging to identify additional systematic misperceptions. Recent work, however, showed that albinism is also associated with an overall bias toward perceiving horizontal rather than vertical motion in bistable stimuli.[38] These results suggest that motion misperception in conditions that include nystagmus may come from a combination of low-level sources like abnormal eye movements and higher-level sources like prior expectations.

The range of acuity and contrast sensitivity levels associated with albinism allowed us to characterize motion perception in individuals with varying levels of overall visual sensitivity, but also adds complexity to interpreting the underlying reasons for the individual differences in motion misperception that we observed. For example, three of the participants with low vision did not report consistent biases in the perceived motion direction (OA, OAG, OC1). One possible explanation for a lack of bias is that they simply were not performing the task and were randomly guessing. This could be the case, for example, if the task was too challenging. Indeed, participants OAG and OC1 did have the lowest acuity and required the highest contrast for the rhombus to be visible. However, participant OA had higher acuity than participants OAG and OC1 and normal contrast sensitivity. In addition, an examination of the raw response data from these three participants shows that their responses varied consistently with the stimulus motion direction. Although participants OA and OC1 did not always perceive the stimulus motion when it moved slowly, they still reported motion percepts on the majority of trials. Thus, we suggest that these three participants were truly less susceptible to underestimating the speed of moving targets, perhaps due to differences in their visual experience, their interpretation of visual cues, or their response strategy.

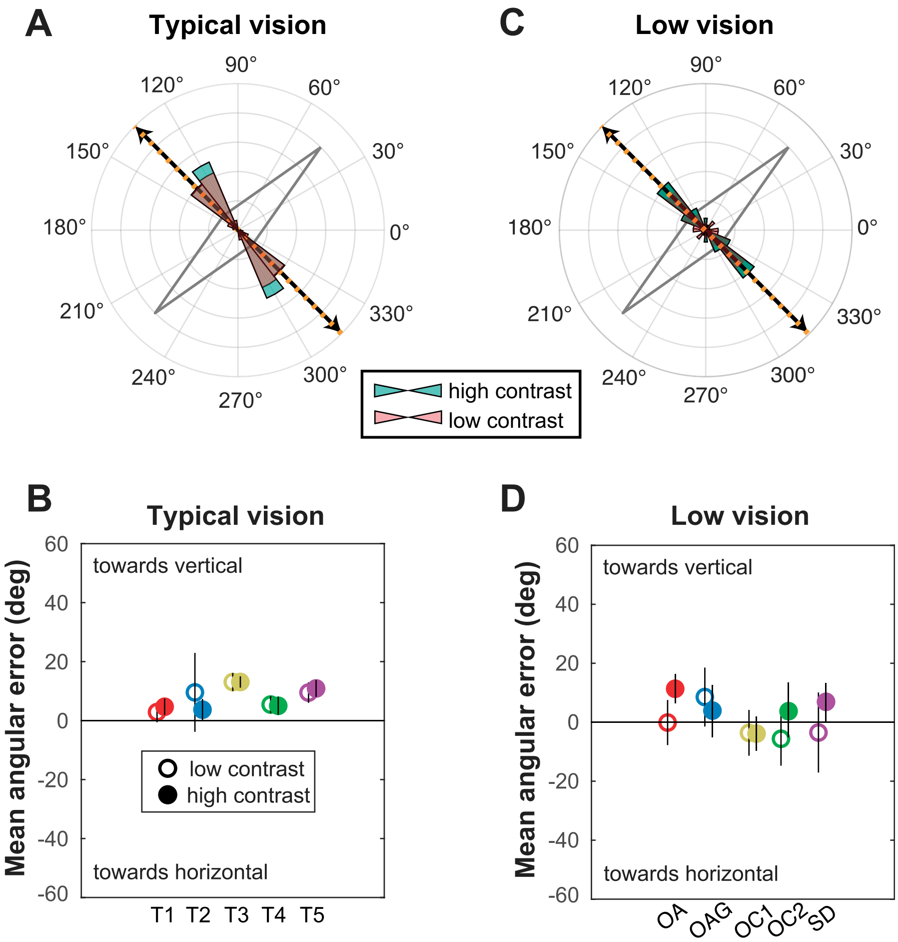

FIGURE 4. Motion direction responses and errors for trials when the rhombus moved diagonally. (A) The polar histogram shows the motion direction responses, in the same format as Figs. 2 and 3, for trials in which the ground-truth motion direction was orthogonal to the long axis of the rhombus, pooled across all participants with typical vision. For this motion, the Bayesian bias prediction is identical to the true direction of motion. Each polar histogram has a radius of 0.5 in units of probability. (B) Mean and 95% confidence intervals are shown for the combined angular error for each participant on all trials, including both directions of diagonal motion. For this plot, the errors are combined over the two diagonals such that positive values indicate errors biased toward vertical and negative values indicate errors in the opposite direction. Participants are individually color coded as in previous figures. (C) and (D) same as in (A) and (B), but for the participants with low vision.

Next, we turn to the two participants with low vision who were consistently biased in their motion percepts (SD and OC2). Interestingly, these individuals had similar biases for both high- and low-contrast stimuli. This was surprising because the manipulation of stimulus contrast dramatically affected all participants with typical vision. We wondered whether an inability to clearly resolve the rhombus edges in both the high- and low-contrast conditions might explain this more general bias. Thus, we made a video of our stimulus with increasing blur to simulate the effects of low acuity. We include this video for demonstration purposes as Supplemental Video 2, available at http://links.lww.com/OPX/A735 (it was not shown to the study participants). With increasing blur, the edges of the rhombus become harder to localize, and provisionally, the motion illusion seems to occur. Thus, we propose that low acuity may also induce motion biases, independent of physical stimulus contrast. However, we cannot yet explain why this affected two participants and not the others. Participant SD was the only participant with late onset of visual impairment (due to Stargardt disease), and it is appealing to consider that previous normal visual experience led them to develop biases more similar to people with typical vision. However, this rationale cannot be applied to participant OC2, who had low vision since birth. Thus, although this dataset does not support any strong generalizations about the role of experience in motion perception, it does provide a foundational characterization of the types of differences in motion perception that people with low vision may experience.

Understanding people's perceptions and misperceptions is essential for providing informed clinical guidance and for designing effective rehabilitation strategies and assistive technology. For example, if one knows that percepts of motion may be biased in addition to being unreliable, an assistive device or training paradigm for safe navigation could incorporate information to encourage people to rely less on prior expectations or to remind them that moving pedestrians may appear slower than they actually are. It may even be possible to counteract these biases in advanced assistive technology, for example, by creating visual augmentations that speed up the apparent motion of dynamic obstacles that are detected and tracked using computer vision. However, such visual augmentations would need to be carefully customized to the visual motion perception of each user. Even if not every patient with low vision will have the experience of underestimating speeds, informing patients about the possibility of speed and motion misperceptions may provide a valuable addition to the clinical toolkit.

Our study design was motivated by the Bayesian inference framework, which ascribes perceptual biases to an unconscious probabilistic inference process in which people rely more heavily on their prior expectations when their sensory information is less reliable (e.g., when targets are hard to see). How does this work inform the way we think about Bayesian inference? The Bayesian inference framework provides a principled, quantitative model that explains a range of other perceptual biases that occur when vision is reduced.[17] However, our work highlights the fact that Bayesian frameworks rely on our ability to understand people's prior expectations. These prior expectations might be shaped by different histories of perceptual experiences in people with low vision. Furthermore, the diversity of conditions causing low vision might lead to additional variation in the prior expectations of low-vision populations, driving larger individual differences than in the population of people with typical vision. As such, our experimental paradigm constitutes a promising method for understanding the underlying mechanisms by which various low-vision conditions affect motion perception. Bayesian models have advanced to the point that prior expectations can be modeled quantitatively based on psychophysical data.[44–46] If visual priors vary across different forms of low vision, there is great potential to characterize these differences in detail by combining our experimental paradigm with recent Bayesian models.

At the same time, researchers have identified other stimulus features beyond visibility, such as chromatic content and visual context, which can lead to speed misperceptions.[20,47] On the computational side, in addition to Bayesian models, researchers have proposed alternative explanations for these slow-speed biases that do not rely on prior expectations at all.[18–20] Our work suggests that such alternative accounts for perceptual biases should necessarily incorporate factors that can account for individual differences between populations.

There are many areas in which future work can build on our results. For example, we did not systematically characterize the contrast sensitivity functions or nystagmus patterns of the research participants. More detailed characterizations of visual function may help explain the types of individual differences we observed in terms of visual sensitivity rather than in terms of prior assumptions. Our sample size was also small and dominated by individuals with albinism, which limits our ability to make broad generalizations about low vision and motion perception. However, given the diversity of visual characteristics and function associated with low-vision conditions, we expect that misperception patterns may be highly individualized. Additional customization of the stimulus parameters to ensure robust visibility even with low contrast would help support the assessment of motion misperception across larger sample sizes. Research on larger cohorts of participants would therefore be helpful for understanding both the general trends and the diversity of misperceptions that people with low vision may experience in daily life.

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