Motion Misperception in Anisomyopia Before and After Optical Correction

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Purpose. To investigate interocular delay in anisomyopes at different spatial frequencies.

Methods. Interocular delay (difference in processing speeds between eyes) was measured psychophysically in 21 anisomyopes (observers with a large refractive difference), 20 isomyopes, and 19 emmetropes at 0.5, 1, and 2 cycles per degree (c/deg). During the visual task, small Gabor elements with lateral movements were shown to both eyes. When interocular delay was present, the stimuli created an illusory percept of a cylinder rotating in depth (motion misperception) despite no depth cues. Anisomyopes and isomyopes were tested before and after optical correction; emmetropes were tested only before. Clinical differences between eyes in anisomyopes, including axial length, visual acuity, and spherical equivalent, were also measured.

Results. Anisomyopes showed interocular delay at 2 c/deg, with the more myopic eye faster before optical correction (Cohen's $d = 0.48$), correlating with clinical differences ($P < 0.05$). Optical correction abolished this delay at 2 c/deg. At 0.5 and 1 c/deg, anisomyopes showed no delay before optical correction, although there were spatial differences between the eyes. Surprisingly, they showed interocular delay after optical correction (more myopic eye faster) when the images of both eyes were spatially equal ($P < 0.05$). Isomyopes and emmetropes showed no interocular delay at any spatial frequency before and after optical correction.

Conclusions. Anisomyopes experience motion misperception at 2 c/deg before optical correction and at 0.5 and 1 c/deg after correction, suggesting optical and neural origins of interocular delay. Tailored interventions based on clinical characteristics may help improve visual function such as motion perception.

Keywords: anisomyopia, pulfrich effect, interocular delay, spatial frequency, blur

When two eyes combine visual information, they form a single representation of the world with depth. Depth is encoded from binocular disparity, which refers to the difference in the positions of the image of an object on the retinas of the two eyes.[1–3] Carl Pulfrich first described a related phenomenon: the misperception of depth for moving objects without depth cues.[4] This visual illusion now bears his name. The Pulfrich effect occurs when two eyes encode visual information at different speeds (interocular delay), creating a sense of depth. Lit[5] demonstrated that different luminance levels to different eyes could trigger the Pulfrich effect by creating processing speed differences between eyes, resulting in binocular disparity. As this binocular disparity increases, the perceived degree of depth from interocular delay also increases.[6]

Researchers have reexamined this century-old depth illusion since the late 2010s using new psychophysical methods.[7–10] Their findings reveal that differences in the clarity of the images perceived by each eye, such as contrast and spatial frequency, can trigger the Pulfrich effect in unexpected ways.[7,10,11] For example, higher contrast in one eye has been associated with faster processing,[10] yet Burge et al.[7] found the opposite: The more blurred eye (lower contrast) processed information faster. Min et al.[11] further reported that differences in spatial-frequency components between the eyes' images could trigger the Pulfrich effect, with clearer images (higher spatial frequency) being processed more slowly. Decades-old studies also linked high spatial frequency to perceptual and electrophysiological delays in the occipital lobe.[12–14] Together, these studies have questioned whether optical corrections such as monovision for presbyopia[7,15] might induce the Pulfrich effect by disrupting binocular vision.

Natural causes can introduce clarity mismatches (spatial frequency and contrast) between the eyes' images. For example, anisometropia is a condition where the refractive error (spherical equivalent [SE]) differs by at least 1.00 diopter (D) between eyes.[16–19] Myopic anisometropia (anisomyopia), caused mainly by asymmetrical axial lengths, involves a myopic SE difference of at least 1.00 D between eyes.[20–22] In anisomyopia, visual processing speed may differ between eyes due to unequal refractive error. For some anisomyopes using optical correction, unequal ciliary muscle thickness has been reported, potentially causing slight differ-

ences in accommodation and refractive error.[23–25] Additionally, undercorrection due to evolving refraction over time can increase blur in the more myopic eye,[26] removing high spatial frequency components and reducing contrast, which may elicit the Pulfrich effect. The anisomyopic visual system may undergo calibration to offset interocular delay from refractive error differences. Visual adaptation to blur lowers blur sensitivity[27] and can affect both eyes,[28] potentially balancing apparent contrast despite differences in spatial clarity between eyes. This long-term adaptation (calibration), which capitalizes on neural plasticity in the visual cortex,[29,30] might reduce interocular differences in processing speeds. However, after calibration, restored clarity through optical correction may induce interocular delay when evenly matched images are perceived with different levels of apparent contrast.

In this study, we used a psychophysical method[10] to measure interocular delay in anisomyopes, as well as those with smaller refractive error differences or better vision, such as isomyopes and emmetropes respectively, across a range of spatial frequencies (up to 2 c/deg) that predominate in natural images.[31] Low spatial frequency spectra of images contribute significantly to motion and spatial binding through the magnocellular pathway.[32] If interocular delay is present at low spatial frequencies, inducing the Pulfrich effect, the position of a quickly moving target can be misperceived, potentially increasing the risk of aviation or traffic accidents.[7] Our investigation focuses on whether the Pulfrich effect occurs at low spatial frequencies in anisomyopic populations with interocular blur differences. We examined two potential causes of the Pulfrich effect in anisomyopes:

1. Optical cause—We explored whether interocular blur differences from refractive error induce the Pulfrich effect in uncorrected anisomyopes. We hypothesized that the blurrier eye would process information faster, consistent with previous studies,[7,11] and that the Pulfrich effect would correlate with refractive error differences, indicating an optical cause.
2. Neural cause—We tested whether the anisomyopic visual system had undergone neural calibration. Neural calibration would be evidenced by the absence of the Pulfrich effect despite interocular differences in spatial frequency or contrast (no optical correction) and its presence when these differences were eliminated (optical correction), suggesting its neural origin.

Methods

Participants

Twenty-one anisomyopes, 20 isomyopes, and 19 emmetropes participated in the study (60 subjects total). Their detailed information is provided in Table 1. Previous studies on processing delays have recruited three to 20 subjects per subject group,[7,33,34] demonstrating a high statistical power despite small to moderate sample sizes. This is because psychophysical measurements require a large number of trials to obtain a single data point for each subject in each condition,[35] thereby reducing measurement variability and boosting statistical power.

Each subject group had unique criteria for eligibility. First, for emmetropia, the SE had to be within −0.25 D to +0.75 D[36] and uncorrected visual acuity ≤ 0.00 logMAR. For isomyopia, the difference in myopic SE between the two eyes was <1.00 D, and the best-corrected visual acuity (BCVA) was ≤0.00 logMAR.[20] For anisomyopia, the minimum interocular difference in myopic SE between the eyes was 1.00 D, and the BCVA was ≤0.00 logMAR, which was widely used in other studies.[19,20,37] Anisomyopes with larger interocular differences in SE failed to perform this experiment (poor psychometric function), likely due to problems in binocular fusion. All subjects were between 18 and 30 years old, an age range that matches previous studies[19,38] and has lower incidences of age-related eye diseases and other abnormalities in ocular structure or function.[39] We matched the mean SE across both eyes of anisomyopes and isomyopes, $t(34.4) = 1.02$, $P = 0.313$ (independent samples t-test), and sex ratios across all three groups, Pearson's $\chi^2(2, n = 60) = 5.54$, $P = 0.0626$. These results indicate that the blur levels of the two clinical groups and ratios of sex across all three groups were similar. Exclusion criteria were also established, including high myopia with SE ≤ −6.00 D, astigmatism with the rule < −1.50 D, astigmatism against the rule < −1.00 D, oblique astigmatism < −1.00 D, or a history of ocular or systematic disease and ocular surgery.

The study adhered to the tenets of the Declaration of Helsinki and was approved by the ethics committee of the Eye Hospital, Wenzhou Medical University (approval number: 2022-162-K-127-01). Except for one subject (primary author MC), all subjects were naïve to the purpose of the study and provided written informed consent. Statistical results remained consistent whether the data of the primary author were included or excluded.

Table 1. Clinical Information for All Participants

Group	Anisomyopia	Isomyopia	Emmetropia
N	21	20	19
Age (y), mean ± SD	23.3 ± 1.48	23.6 ± 2.06	23.1 ± 3.49
Sex, *n*			
Female	18	15	10
Male	3	5	9
SE (D), mean ± SD	−2.31 ± 1.04	−2.72 ± 1.45	0.115 ± 0.183
More myopic	−3.25 ± 1.12	—	—
Less myopic	−1.37 ± 1.10	—	—
Interocular SE (D) difference, mean ± SD	1.88 ± 0.763	0.356 ± 0.230	0.283 ± 0.224
Axial length (mm), mean ± SD	24.2 ± 0.803	24.6 ± 0.920	23.5 ± 0.664
Longer	24.5 ± 0.832	—	—
Shorter	23.8 ± 0.802	—	—
Corneal curvature (D), mean ± SD	43.8 ± 1.13	43.4 ± 1.02	42.7 ± 1.41
Stereopsis (arcsec), mean ± SD	55.2 ± 19.9	49.0 ± 35.8	44.2 ± 8.38

Clinical Assessment

For all three subject groups, subjective refraction was performed without cycloplegia for adults,[19,40] including initial maximum plus to maximum visual acuity (MPMVA), initial duochrome (red–green test), Jackson cross cylinder test, second monocular MPMVA for each eye, and finally binocular balance for both eyes. In each MPMVA, a fogging technique was used to relax accommodation. Although we did not perform cycloplegic refraction, the fogging technique and binocular balance in subjective refraction helped adult subjects to relax their accommodation; the measurement with non-cycloplegic subjective refraction has been shown to have an excellent agreement with that of cycloplegic refraction.[40] Visual acuity was measured using the logarithmic visual acuity chart Early Treatment Diabetic Retinopathy Study (ETDRS) at the standard distance of 4 meters.

Apparatus

The experiment was performed on a Lenovo desktop computer (Lenovo Group, Beijing, China) with an HD Graphics 530 graphics card (Intel Corporation, Santa Clara, CA, USA). It was displayed on a gamma-corrected 27-inch light-emitting diode (LED) monitor (LG Life Science, Seoul, Korea) with a resolution of 1920 × 1080 pixels and a refresh rate of 60 Hz.[33] Subjects viewed the monitor dichoptically through passive polarized glasses. The experiment was conducted using MATLAB R2021a (MathWorks, Natick, MA, USA) and Psychtoolbox-3.[41]

A KR-800 Auto Kerato-Refractometer (Topcon Co., Tokyo, Japan) was used to measure the subjects' corneal curvature, which was measured 10 times and then averaged. The Topcon IS-600 refraction unit was used for subjective refraction. The Lenstar LS 900 (Haag-Streit, Koeniz, Switzerland) was used to measure the axial length (three times total). Soft contact lenses (Bausch & Lomb, Vaughan, ON, Canada) were used to correct isomyopia and anisomyopia. Contact lenses do not prevent aniseikonia (unequal retina image size) but reduce it more effectively than spectacles,[42] and aniseikonia does not affect interocular delay.[10] Yan's stereo random dot book was used to assess stereoacuity.[33]

Stimuli and Procedure

This study used a psychophysical method to measure interocular processing delays (Fig. 1A).[10] Each trial began with a gray background and a fixation point, remaining until the subject pressed a key to proceed. A rotating cylinder stimulus (18° width × 12° height) was then presented for 800 ms to two eyes, creating an illusory depth effect. The cylinder contained 200 Gabor patches, each with a size of 0.3°, random phase, a contrast of 80%, sinusoidal angular speed of 18°/s, and a spatial frequency of 0.5, 1, or 2 c/deg. The rotation direction of the cylinder (clockwise or anticlockwise) depended on the interocular phase difference (Figs. 1B, 1C). Subjects reported the perceived rotation direction using a keyboard: the right arrow key if the area of the cylinder close to the screen appeared to move rightward (counterclockwise rotation), and the left arrow key if it appeared to move leftward (clockwise rotation). The interocular phase differences were −1.5°, −0.75°, −0.375°, −0.1875°, −0.0938°, −0.0469°, −0.0234°, 0°, 0.0234°, 0.0469°, 0.0938°, 0.1875°, 0.375°, 0.75°, and 1.5°. Each interocular phase difference was tested 20 times per block using the method of constant stimuli, following previous studies[11,33,43,44] that demonstrated robust effect sizes and power.[35] Each block took approximately 7 minutes, after which subjects could rest until ready to continue, helping to relieve fatigue that might affect task performance.[45] Psychometric functions were fitted with the Palamedes toolbox using cumulative logistic functions, maximum likelihood procedures, and bootstrapping methods.[46] We estimated the point of subjective equality (PSE), where the perceived rotation of the cylinder appears ambiguous, because the interocular phase difference compensates for the processing speed difference.[47]

There were several experimental conditions (Fig. 2). Isomyopic and anisomyopic subjects with blurry vision were tested in both uncorrected and corrected conditions (in randomized order on different days at similar times). In contrast, emmetropic subjects were tested only in the uncorrected condition. Subjects adapted to contact lenses for 20 minutes before testing.[48] We verified that corrected visual acuity reached ≤0.00 logMAR using the ETDRS acuity chart at 4 meters, confirming clear stimulus visibility both monocularly and binocularly. All subjects were tested at three spatial frequencies (0.5, 1, and 2 c/deg) twice in randomized order, with emmetropic subjects completing 1800 trials and clinical groups completing 3600 trials across all conditions. Before formal testing, each subject performed a 150-trial practice block to familiarize themselves with the visual task. Our pilot experiments suggested that this practice reduced measurement variability. Measurements were conducted in a dimly lit room at a viewing distance of 90 cm.[33]

Data Analysis

PSE values are measured in degrees. A positive PSE indicates the left eye is faster, whereas a negative PSE indicates the right eye is faster. A PSE of 0 indicates that the two eyes are temporally balanced. Additionally, as in a previous study,[34] we converted PSEs to rectified PSEs (rPSEs) based on each subject's SE difference for all subject groups to determine whether the blurrier eye is faster. The conversion followed these rules: If the SE difference (right eye – left eye) was ≥0, then rPSE = PSE; if the SE difference was < 0, then rPSE = −PSE. For anisomyopic subjects, a positive rPSE indicates that the more myopic eye (the blurrier eye) is faster than the less myopic eye, whereas a negative rPSE suggests that the more myopic eye is slower. The data were analyzed and visualized using R software (R Foundation for Statistical Computing, Vienna, Austria),[49] with the *ggplot2*[50] and *smplot2* packages.[51]

Statistical Analysis

The Shapiro–Wilks test was used to test for normality. A linear mixed-effects model was used to analyze the effect of subject group (anisomyopia, isomyopia, emmetropia), spatial frequency (0.5, 1, 2 c/deg), and viewing condition (uncorrected, corrected) on rPSE using the lmer() function from the *lme4* package in R.[43,52–54] The model incorporated fixed effects for subject group, viewing condi-

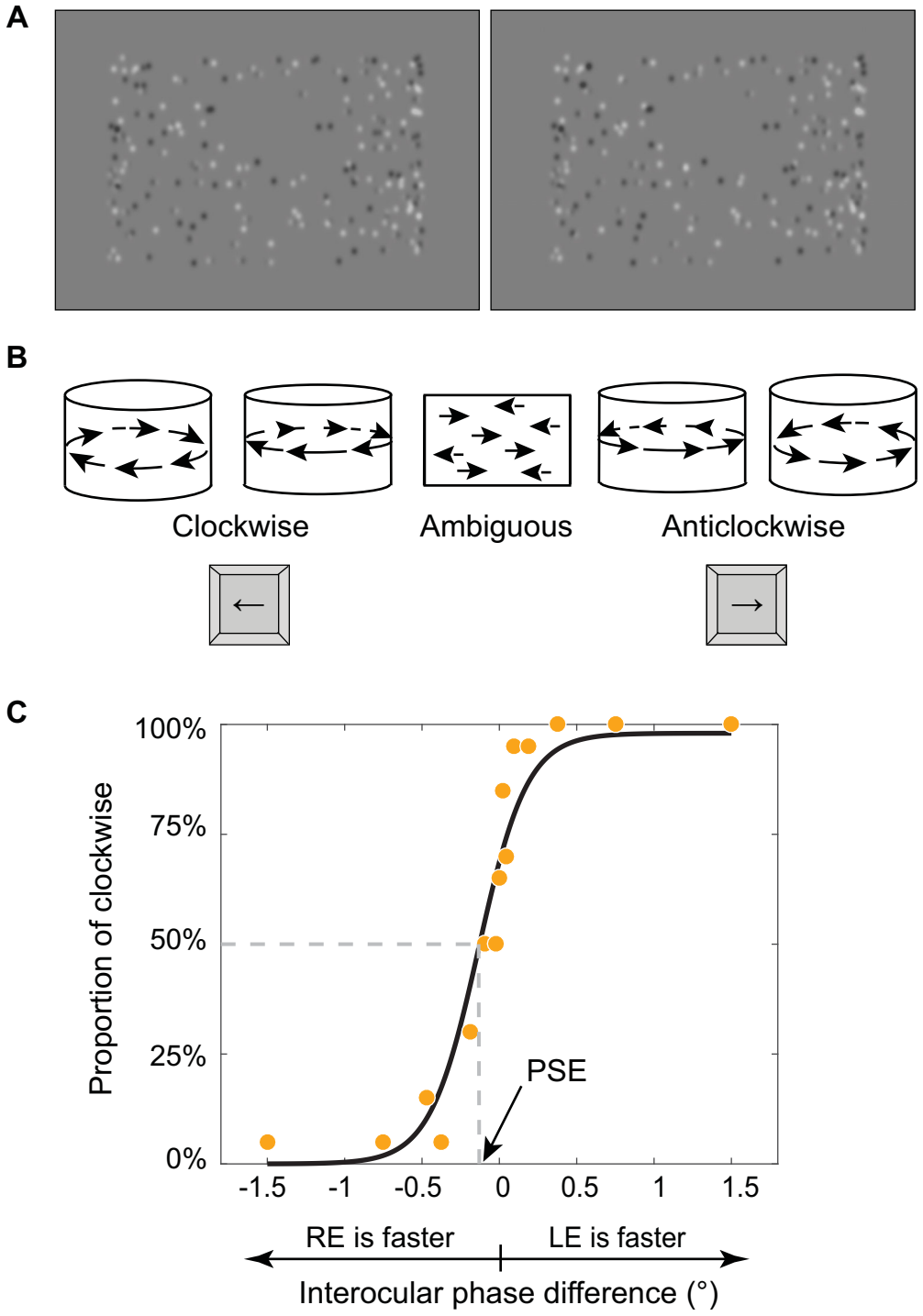

Figure 1. Illustration of the visual task and data analysis. (**A**) Two eyes were dichoptically presented with horizontally moving Gabor elements, forming a rotating cylinder. (**B**) The interocular phase difference between the stimuli shown to the two eyes and interocular delay determined the perceived rotation of the cylinder. The interocular phase differences were −1.5°, −0.75°, −0.375°, −0.1875°, −0.0938°, −0.0469°, −0.0234°, 0°, 0.0234°, 0.0469°, 0.0938°, 0.1875°, 0.375°, 0.75°, and 1.5°. Subjects were given two response choices to report clockwise or anticlockwise rotation of the stimulus. (**C**) The interocular phase difference corresponding to 50% of clockwise responses (i.e., ambiguous perception) was defined as the PSE. A positive PSE indicates faster left eye (LE) processing, and a negative PSE indicates faster right eye (RE) processing. This graph shows data from one representative subject.

tion, spatial frequency, and their interactions, with a random effect for subjects to account for their repeated measures. This approach addresses the mismatch in conditions between the clinical and control groups. Additionally, we performed one-sample *t*-tests or Wilcoxon signed-rank tests to determine whether the rPSEs of each group under specific conditions were significantly different from zero. These comparisons revealed whether inte-

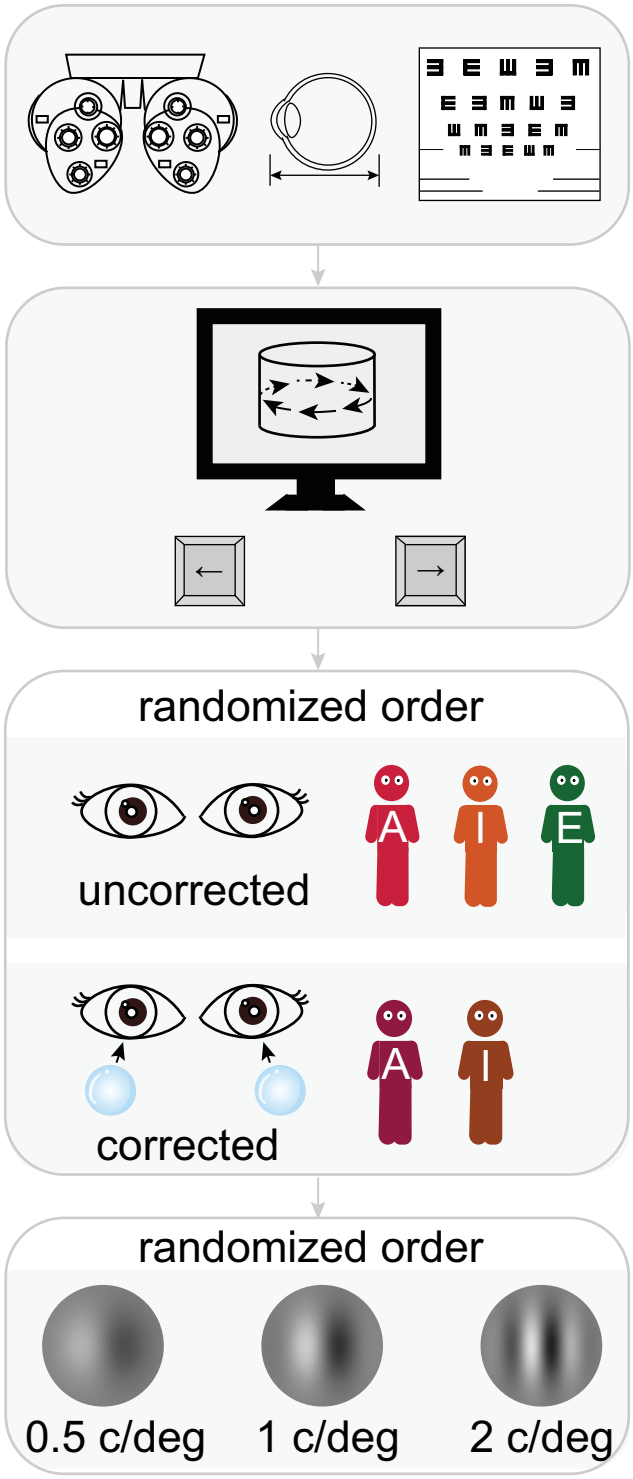

Figure 2. Procedure for the experiment. Anisomyopes, isomyopes, and emmetropes were asked to undergo clinical assessment first, including subjective refraction, axial length, visual acuity, stereopsis, and corneal curvature measurements. Participants then completed a practice test block (150 trials) of the visual task to be used in the experiment. After familiarization with the task, anisomyopes and isomyopes participated in sessions both before and after optical correction with soft contact lenses, whereas emmetropes participated only in uncorrected conditions. Testing occurred randomly at three spatial frequencies (0.5, 1, and 2 c/deg), with each spatial frequency tested twice. A, anisomyopes ($n = 21$); I, isomyopes ($n = 20$); E, emmetropes ($n = 19$). In total, each emmetropic observer completed 1800 trials, and each anisomyopic and isomyopic observer completed 3600 trials.

rocular delays were significant within each group under various conditions and which eye processed information faster, following the methodology from the previous study.[34] A Spearman correlation test was used to investigate the relationship between PSE and clinical characteristics (the difference in axial length, the difference in visual acuity, the difference in SE, and the difference in corneal curvature).

Results

Interocular Delay (rPSE) of all Groups

Linear Mixed-Effects Model Using all Data. We used a linear mixed-effects model to examine how the subject group, viewing condition, spatial frequency, and their interactions affected rPSE (Fig. 3, Table 2). The analysis revealed a variance of 0.00586 for the random intercept of subjects and 0.0111 for residual variance, indicating subject-level differences contributed to rPSE variability. Our fixed-effects analysis yielded three key findings. First, anisomyopes exhibited greater rPSE after optical correction ($\beta = 0.107$, $P = 0.0232$). Second, anisomyopes showed larger interocular delay than emmetropes at 2 c/deg ($\beta = 0.112$, $P = 0.0187$) in general. Third, and most importantly, a significant three-way interaction emerged (anisomyopia × spatial frequency at 2 c/deg × after correction; $\beta = -0.181$, $P = 0.00659$), revealing that the effect of optical correction at 2 c/deg was significant in anisomyopes but not in other subject groups. In other words, the optical correction would reduce interocular delay by 0.181° in rPSE at 2 c/deg only in anisomyopes. To summarize, interocular delay in anisomyopes differs significantly from that in emmetropes (controls) at 2 c/deg, with optical correction significantly reducing this delay. However, interocular delay was larger in anisomyopes after optical correction across all spatial frequencies, particularly at lower spatial frequencies (0.5 and 1 c/deg). These findings demonstrate spatial frequency dependency

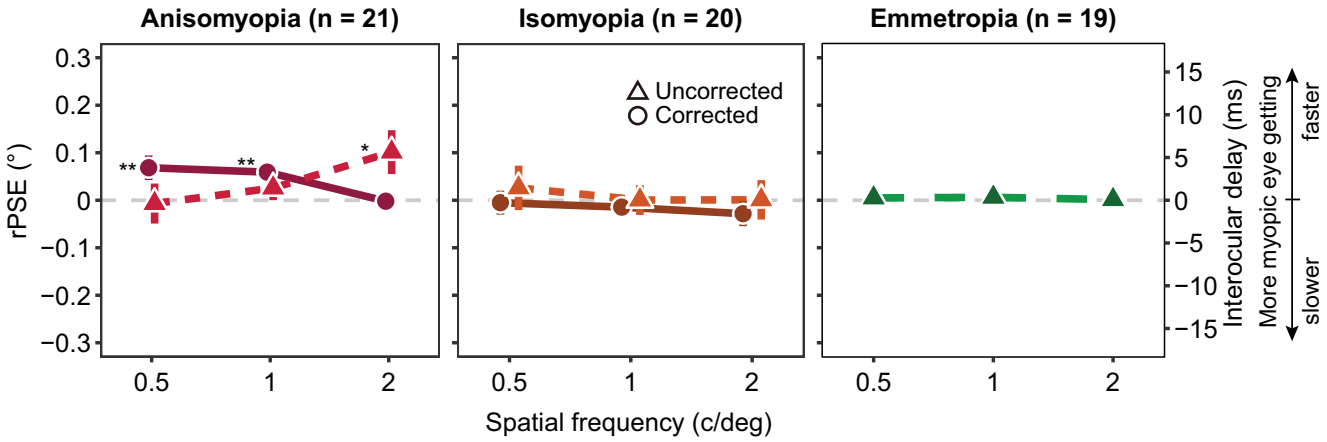

Figure 3. rPSE of the three groups at different spatial frequencies. We calculated rPSE from PSE based on the SE difference. When the SE difference was ≥0, rPSE = PSE; when the SE difference was <0, rPSE = −PSE. For anisomyopia, a positive rPSE indicates faster processing in the more myopic eye, whereas a negative rPSE indicates slower processing in the more myopic eye. The second axis (*right side*) translates rPSE values (deg) into interocular delay (ms). *Error bars* represent standard error. *$P < 0.05$, **$P < 0.01$ (one-sample *t*-tests or Wilcoxon signed-rank tests).

Table 2. Linear Mixed-Effects Model Using all Data

Random Effects	**Variance**	**SD**			
Subject	0.00586	0.0766			
Residual	0.0111	0.106			
Fixed Effects	**Estimate (β)**	**Standard Error**	***df***	***t***	***P***
Intercept	0.00487	0.0299	198.5	0.163	0.871
Group					
Anisomyopia	−0.0118	0.0413	198.5	−0.286	0.775
Isomyopia	0.0212	0.0418	198.5	0.507	0.613
Emmetropia (reference)	—	—	—	—	—
After correction (reference: before)	−0.0312	0.0334	236.8	−0.934	0.351
Spatial frequency (c/deg)					
2	−0.00359	0.0342	236.8	−0.105	0.917
1	0.00138	0.0342	236.8	0.0400	0.968
0.5 (reference)	—	—	—	—	—
Anisomyopia × after correction	**0.107**	**0.0466**	**236.8**	**2.29**	**0.0232***
Anisomyopia × SF at 1 c/deg	0.0313	0.0472	236.8	0.662	0.508
Isomyopia × SF at 1 c/deg	−0.0270	0.0478	236.8	−0.564	0.573
Anisomyopia × SF at 2 c/deg	**0.112**	**0.0472**	**236.8**	**2.368**	**0.0187***
Isomyopia × SF at 2 c/deg	−0.0216	0.0478	236.8	−0.452	0.651
After correction × SF at 1 c/deg	0.0162	0.0472	236.8	0.344	0.732
After correction × SF at 2 c/deg	0.00200	0.0472	236.8	0.0420	0.966
Anisomyopia × SF at 1 c/deg × after correction	−0.0582	0.0659	236.8	−0.883	0.378
Anisomyopia × SF at 2 c/deg × after correction	**−0.181**	**0.0659**	**236.8**	**−2.74**	**0.00659****

Bolded rows indicate statistically significant results.
* $P < 0.05$.
** $P < 0.01$.

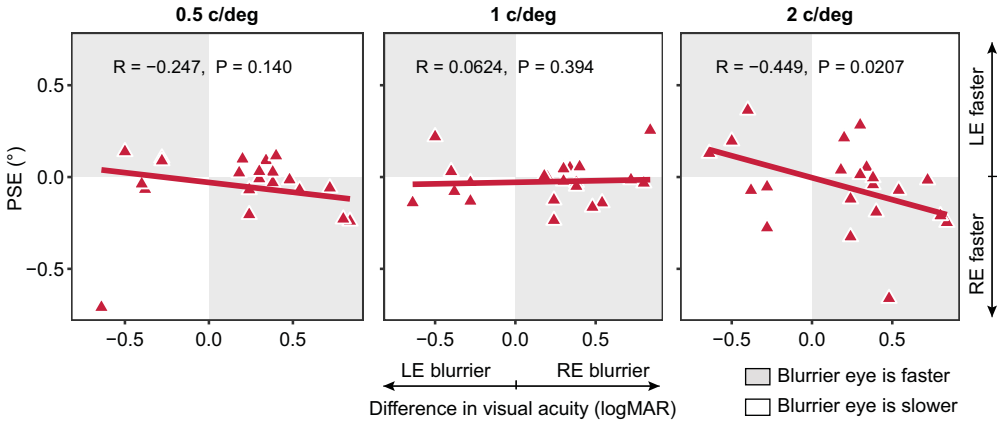

Figure 4. Scatterplot of correlation between PSE and difference in visual acuity in uncorrected anisomyopia at each spatial frequency. The correlation method is Spearman correlation, with the one-tailed *P*-value reported. The *shadowed area* means the blurrier eye is faster. LE, left eye; RE, right eye.

of interocular delay and its response to optical correction in anisomyopes.

One-Sample *t*-Tests and Wilcoxon Signed-Rank Tests

Finally, we examined whether the magnitude of interocular delay was significant using one-sample *t*-tests and Wilcoxon signed-rank tests. In anisomyopes, the more myopic eye processed visual information significantly faster than the less myopic eye (rPSE > 0) at 2 c/deg before optical correction, $t(20) = 2.20$, $P = 0.0400$, Cohen's $d = 0.479$ (two-tailed one-sample *t*-test), but not at lower spatial frequencies (0.5 and 1 c/deg). Optical correction eliminated this delay at 2 c/deg, $t(20) = -0.105$, $P = 0.917$, Cohen's $d = -0.0229$ (two-tailed one-sample *t*-test). Surprisingly, after optical correction, the more myopic eye processed information faster than the less myopic eye in anisomyopes at 0.5 and 1 c/deg: at 0.5 c/deg, $P = 0.00554$ and Wilcoxon effect size = 0.588 (Wilcoxon signed-rank test); at 1 c/deg, $t(20) = 3.10$, $P = 0.00565$, and Cohen's $d = 0.676$ (two-tailed one-sample *t*-test). This finding suggests a possible neural calibration of the visual system where binocular spatiotemporal information is processed. Neither isomyopes nor emmetropes showed interocular delay before or after optical correction ($P > 0.05$, two-tailed one-sample *t*-tests). In summary, anisomyopes exhibited interocular delay (rPSE) at 2 c/deg before optical correction and at low spatial frequencies (0.5 and 1 c/deg) after optical correction.

Correlations Between PSE and Clinical Characteristics in Anisomyopic Observers

Correlation Between PSE Before Optical Correction and Clinical Differences Between the Eyes. We evaluated whether optically driven spatial differences between the eyes correlate with interocular delay in uncorrected anisomyopic observers. Our hypothesis predicted that the more myopic (blurrier) eye would have a faster processing speed. Using one-tailed Spearman correlation tests, we examined the relationship between PSE and clinical characteristics in uncorrected anisomyopic observers. Results revealed a stronger negative correlation between PSE and visual acuity difference between the eyes at 2 c/deg (one-tailed Spearman correlation, 0.5 c/deg: $R = -0.247$, $P = 0.140$; 1 c/deg: $R = 0.0624$, $P = 0.394$; 2 c/deg: $R = -0.449$, $P = 0.0207$) as shown in Figure 4. This finding indicates that at higher spatial frequencies, the blurrier eye processes visual information faster in uncorrected anisomyopes.

We further investigated the relationship between PSE and the SE difference in uncorrected anisomyopes, with similar results. Our analysis demonstrated that a larger SE difference correlates with a larger interocular delay, where the blurrier eye showed faster processing at 2 c/deg (one-tailed Spearman correlation, 0.5 c/deg: $R = 0.236$, $P = 0.151$; 1 c/deg: $R = -0.0553$, $P = 0.406$; 2 c/deg: $R = 0.393$, $P = 0.0389$). Similarly, the relationship between PSE and axial length difference showed that the longer eye (hence, blurrier) processed stimuli faster at 2 c/deg (one-tailed Spearman correlation, 0.5 c/deg: $R = -0.264$, $P = 0.123$; 1 c/deg: $R = 0.104$, $P = 0.327$; 2 c/deg: $R = -0.452$, $P = 0.0198$). Collectively, these findings indicate that clinical characteristics can predict which eye (blurrier/longer) processes information faster and the degree of interocular delay. However, no correlation emerged between PSE and corneal curvature difference (one-tailed Spearman correlation, 0.5 c/deg: $R = 0.0207$, $P = 0.464$; 1 c/deg: $R = 0.159$, $P = 0.245$; 2 c/deg: $R = 0.0361$, $P = 0.438$).

Correlation Between PSE After Optical Correction and Clinical Differences Between the Eyes. We also investigated the relationship between PSE and clinical characteristics of anisomyopes after optical correction. Specifically, we sought to identify predictive factors for the degree of neural calibration that caused interocular delay at low spatial frequencies (0.5 and 1 c/deg) despite equalizing spatial differences between the eyes. Having no clear initial hypothesis, we performed a two-tailed Spearman correlation test. Results revealed a significant positive correlation between corrected PSE and original SE difference at 0.5 c/deg (two-tailed Spearman correlation, 0.5 c/deg: $R = 0.513$, $P = 0.0174$; 1 c/deg: $R = 0.394$, $P = 0.0773$). Additionally, we observed a similar relationship between corrected PSE and axial length difference at 0.5 c/deg (two-tailed Spearman correlation, 0.5 c/deg: $R = -0.466$, $P = 0.0333$; 1 c/deg: $R = -0.297$, $P = 0.191$). These findings indicate that the previously more myopic (blurrier and longer) eye processed information faster after optical correction at a very low spatial frequency (0.5 c/deg).

Discussion

We investigated if anisomyopes had interocular delay due to spatial (blur) differences between the eyes (optical cause) that reflected their clinical characteristics. We also examined whether their visual system had calibrated (neural cause) to offset interocular delay that would otherwise occur from the optically driven spatial frequency differences between eyes. To summarize, we observed that anisomyopes exhibited interocular delay both before and after optical correction, with evidence indicating that there are both optical and neural origins of the Pulfrich effect.

Optical Cause of the Pulfrich Effect

Before optical correction, as hypothesized, the more myopic eye processed information significantly faster at 2 c/deg in anisomyopes, indicating that removing relatively higher spatial frequency components enhanced the eye's processing speed. This delay at 2 c/deg was abolished entirely by optical correction, which minimized differences in spatial frequency between the two eyes. In contrast, there was no interocular delay in uncorrected anisomyopes at low spatial frequencies (0.5 and 1 c/deg). Moreover, isomyopes (uncorrected or corrected) and emmetropes exhibited no interocular delay at any spatial frequency. These results demonstrate that differences in the optics between eyes, which induce interocular blur differences, elicited the Pulfrich effect, causing the blurrier eye to process information faster in uncorrected anisomyopes at medium (and possibly high) spatial frequencies. It was significantly correlated with clinical characteristics that reflected refractive error differences between the eyes, including differences in visual acuity (Fig. 4), axial length, and spherical equivalent.

Neural Cause of the Pulfrich Effect (Neural Calibration)

We found evidence of neural calibration in anisomyopes, as they experienced interocular delay when images of two eyes were spatially matched. After optical correction, significant interocular delay was observed at low spatial frequencies (0.5 and 1 c/deg), with the previously blurrier eye processing information faster despite equally clear images in both eyes. These findings indicate that the anisomyopic brain compensates for interocular delay induced by optically driven spatial differences. Through visual calibration, the brain likely enhances the blurrier eye's contrast response to compensate for blur-induced loss of visual information, thus altering the appearance of its image[55,56] and its processing speed. Studies on contrast and blur adaptation indicate that this process can induce long-lasting perceptual alterations.[29,30,57] Consistent with this mechanism, we found that, after optical correction, the previously blurrier eye processed information faster at low spatial frequencies (0.5 and 1 c/deg), eliciting the Pulfrich effect. This visual calibration (at 0.5 c/deg) correlated with clinical differences between eyes (spherical equivalent and axial length), suggesting that it adaptively and dynamically enhances the processing speed of the more myopic eye. At 2 c/deg, interocular delay was absent after correction in anisomyopes. This likely results from a better perception of medium spatial frequencies in the more myopic eye, balancing faster speed from increased apparent contrast[10,58] with delayed processing of higher spatial frequencies.[11,58]

Implications

Burge et al.[7] introduced the spatial-frequency binding problem, a paradox where, despite different spatial frequencies being encoded at different rates in the early visual cortex,[14] the later visual system seamlessly combines information to perform visual tasks.[59] The adaptive, dynamic process of visual calibration we observed—correlated with individual interocular spatial (blur) differences in anisomyopes—further complicates the spatial-frequency binding problem. These findings challenge our current understanding of motion perception and other arrays of visual functions, as they do not fully account for the role of prior visual experience in driving neural calibration.

Lorenceau and Alais[32] reported that humans perform motion binding better when the target stimulus is processed more by the magnocellular pathway (low spatial frequency, high temporal frequency). Additionally, the visual system

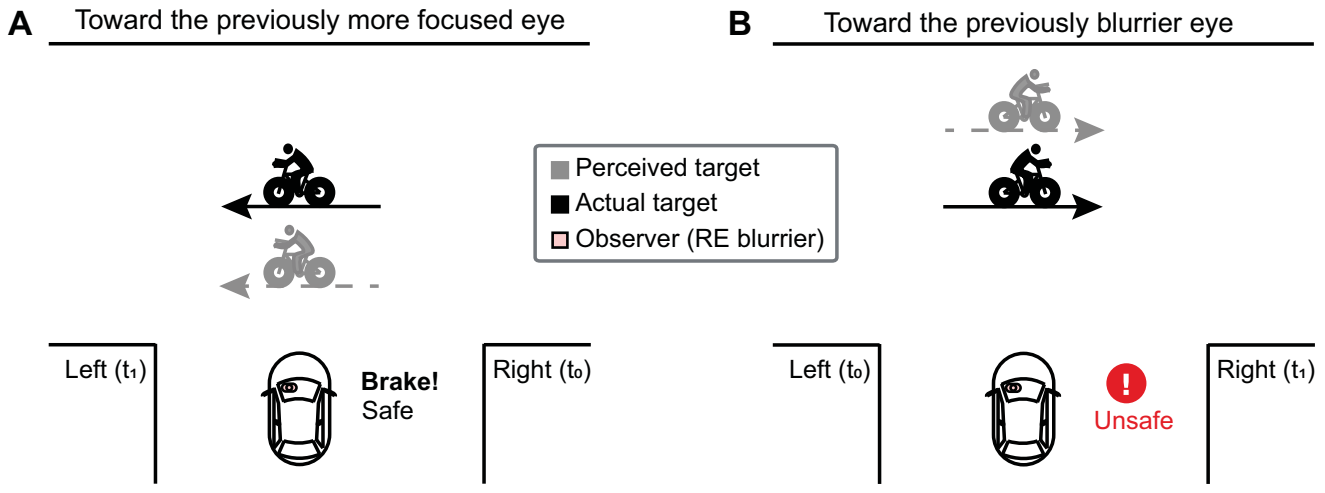

Figure 5. Schematic diagram illustrating the impact of motion misperception on driving safety in the corrected anisomyope, where the right eye was previously blurrier. (**A**) The target (0.5 c/deg) moves toward the previously focused eye (*leftward*). (**B**) The target (0.5 c/deg) moves toward the previously blurrier eye (*rightward*).

is thought to have sustained and transient channels for encoding temporal information.[60–62] The sustained channel processes high spatial frequencies slowly,[63] whereas the transient channel processes low spatial frequencies quickly,[62] enhancing its effectiveness for fast-moving targets. Our results demonstrate that at low spatial frequencies where the magnocellular pathway[64,65] is involved and motion binding is performed best,[32] interocular delay occurs even when spatial characteristics match between the eyes in optically corrected anisomyopes. This delay may cause optically corrected anisomyopes to misestimate relative distances,[7] increasing risks while driving in specific situations. When a target (0.5 c/deg) moves toward the corrected anisomyope's previously more focused eye (Fig. 5A), the driver may underestimate the relative distance, leading to premature braking and avoiding collision. Conversely, when the target moves toward the previously blurrier eye (Fig. 5B), the driver may overestimate the relative distance, risking a collision. Nevertheless, other sources of depth cues, such as binocular disparity from the immediate environment, could help resolve distance ambiguities, reducing risks during driving.

Two stereomotion channels (mechanisms) encode motion-in-depth information[66] and are critical for eliciting the Pulfrich effect[10,67]: changes in binocular disparity over time (CDOTs) or interocular velocity differences (IOVDs). CDOTs track changes in binocular disparity over time as the target moves in depth, whereas IOVDs encode the velocity of the target in each eye separately and computes their difference to determine motion speed and direction. Although mathematically equivalent,[68,69] CDOTs and IOVDs involve distinct neural processes[70] with unique temporal frequency characteristics[71] and function independently in motion-in-depth perception.[72,73] In our sample, anisomyopes showed significantly worse stereoacuity than emmetropes, $H(2) = 7.86$, $P = 0.0196$, $\eta^2 = 0.148$ (Kruskal–Wallis rank-sum test), indicating impaired static binocular disparity detection, which is critical for the CDOT mechanism. Notably, Nefs et al.[74] reported that visually intact observers vary in their reliance on CDOT or IOVD, with some favoring one mechanism over the other. Research shows that patients without stereopsis remain sensitive only to IOVDs.[75] This suggests that anisomyopes may rely more on the IOVD mechanism to perceive motion in depth. The variability in mechanistic preference highlights individual differences in motion-in-depth perception that is also observed in anisomyopic individuals.

Limitations of the Study and Future Directions

Our study has several limitations. First, the study included only moderate anisomyopes, as individuals with severe anisometropia could not perform the task; therefore, the results may not apply to those with severe refractive differences. Additionally, our sample had more female than male anisomyopes, but this imbalance may reflect the natural prevalence of anisomyopia, which is higher in females.[76–78] Finally, higher spatial frequencies remain unexplored, as the small Gabor elements in our stimulus limited reliable testing above 2 c/deg. Researchers have recently used a continuous psychophysical approach to measure interocular delay in normal and clinical populations with a motion-tracking task,[8,79] showing robust reliability and precision. With this approach, researchers could more widely manipulate stimuli parameters, such as spatial frequency, and investigate how they interact with interocular delay. This continuous psychophysical method could also reveal the interaction between each observer's life experience and the degree of visual calibration across a wide-ranging population with different visual conditions that have interocular differences in the spatial clarity of images. Future research should develop new psychophysical methods to parse out IOVD and CDOT contributions to motion-in-depth perception in populations with impaired vision. Tailored interventions, such as motion-in-depth visual training based on the individual's clinical characteristics, may help improve stereopsis and motion perception.

Conclusions

Our study demonstrates that anisomyopic individuals experience motion misperception both before and after optical correction. Interocular delay at medium spatial frequency (2 c/deg) before optical correction aligned with our prediction, as the more myopic eye processed information faster. This delay correlated with interocular differences in clinical characteristics, including visual acuity, axial length, and spherical equivalent. Surprisingly, optically corrected anisomyopes showed interocular delay (with the previously blurrier eye being faster) at low spatial frequencies (0.5 and 1 c/deg), indicating that there was some degree of visual calibration to offset interocular delay that would otherwise occur without correction. Our findings on the effects of optical correction on interocular delay may have implications for traffic safety and illustrate the dynamic and adaptive process by which the visual system adapts to the ever-changing flow of visual information.

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Claude 3.7 Sonnet by Anthropic and ChatGPT 4o by OpenAI were used to enhance the clarity and flow of the text from February 25, 2025, to March 5, 2025.

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