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Characteristics of saccades during the near point of convergence test

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ABSTRACT

The near point of convergence test is widely used to evaluate binocular vision. It assesses the ability of the eyes to converge at short distances. Although the test consists of a pure symmetrical vergence task, small involuntary saccades occur concurrently. The main goal of this study was to analyze saccadic characteristics as a function of vergence demand when testing the near point of convergence. To this purpose, the eye movements of 11 participants were registered with an eye-tracker while they performed the near point of convergence test by following a target that traveled forward and backward on a motorized bench. Saccade amplitude increased and, on average, saccade rate decreased with vergence demand. In general, the direction of the concurrent vergence movement had no significant effect on saccade characteristics. However, each individual subject showed idiosyncratic behavior. Most saccades tended to be corrective in terms of both binocular disparity and individual fixation position errors. In particular, most participants tended to correct the fixation position error of the dominant eye.

1. Introduction

The near point of convergence (NPC) is the nearest point on which the eyes can converge (Scheiman & Wick, 2014). Its assessment is widely used in clinical practice, as a remote NPC value is the sign most frequently used by optometrists for the diagnosis of convergence insufficiency (Rouse, Hyman, & CIRS Study Group, 1997). The NPC is determined by asking the patient to maintain fixation on an object placed in the midline while it is moved toward the patient's eyes. In the objective version of the test, the examiner observes the eyes of the patient to detect when one of them loses fixation. Alternatively, in the subjective version the patient is asked to report diplopia. The distance at which one eye turns out or the patient perceives double vision is the break point of convergence. The recovery point is the distance at which the eyes realign to the target or where the patient reports single vision again. The result of the NPC test typically is reported as the values of both the break and recovery points. The expected values in a young adult population are <5 cm for the break and <7 cm for the recovery (Scheiman et al., 2003). Several authors recommended to repeat the test 4 to 5 times consecutively in order to increase its sensitivity to diagnose convergence insufficiency (Mohindra & Molinari, 1980; Wick, 1987) as symptomatic patients tend to exhibit recession of the NPC with repeated testing whereas asymptomatic patients do not (Davies, 1946; Scheiman et al., 2003).

Provided the fixation target is precisely positioned along the subjects' midline sagittal plane, the assessment of the NPC is a pure symmetrical vergence task. However, even when the target requires pure vergence movements and there is no demand for version, involuntary saccades occur (Collewijn, Erkelens, & Steinman, 1995; Coubard & Kapoula, 2008; Erkelens, Collewijn, & Steinman, 1989; Erkelens, Steinman, & Collewijn, 1989; Kenyon, Ciuffreda, & Stark, 1980; Zee, Fitzgibbon, & Optican, 1992). Although some authors found a higher prevalence of saccades during symmetrical divergence than during symmetrical convergence (Collewijn et al., 1995; Kenyon et al., 1980; Zee et al., 1992), it is generally accepted that the frequency and dynamic characteristics of these versional movements are idiosyncratic (Coubard & Kapoula, 2008; Erkelens, Steinman, & Collewijn, 1989; Zee et al., 1992). Saccades during vergence have been found to be of unequal amplitude in the two eyes (i.e., not perfectly conjugate). Erkelens, Collewijn, & Steinman (1989) concluded that the disjunctive component of the saccades contributed to the "effectiveness" of the vergence movement, suggesting that saccades are not a mere "intrusion" into the

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Table 1
Age, refractive error, phoria at 40 cm, stereopsis and NPC of the participants of the study. NPC values correspond to the mean ± SD of the 3 repetitions using a pen tip as the stimulus. Subject 8 did not report diplopia during the NPC test and could fuse the stimulus up to the nose.

Subject	Age	Refractive error (D)		Phoria (PD)	Stereopsis (arc sec)	NPC (cm)	
		RE	LE			Break	Recovery
1	29	−0.50	Plano	5 eso	16	3.2 ± 0.3	5.3 ± 0.6
2	24	−2.00	−2.00	N/A	12.5	5.0 ± 0	8.2 ± 1.6
3	23	Plano	Plano	2 exo	12.5	3.8 ± 0.3	5.5 ± 0.5
4	23	+0.50 – 0.25 167	+0.50–0.25 173	N/A	23	4.8 ± 0.3	6.3 ± 0.6
5	29	−1.00–0.25 72	−1.00	4 eso	12.5	4.7 ± 0.6	6.2 ± 0.3
6	24	−2.50	−3.50	2 exo	12.5	4.0 ± 0	6.3 ± 0.3
7	26	−6.50	−5.25	1 eso	12.5	3.3 ± 0.6	6.8 ± 0.8
8	25	Plano	Plano	11 eso	23	–	–
9	27	−6.00	−6.00	1 eso	20	2.8 ± 0.3	5.0 ± 1.0
10	25	−1.00–0.75 112	−1.00–0.50 75	1 eso	20	5.3 ± 0.6	8.3 ± 1.5
11	24	Plano	Plano	2 exo	20	2.8 ± 0.3	7.0 ± 0

eso: esophoria. exo: exophoria. N/A: not available.

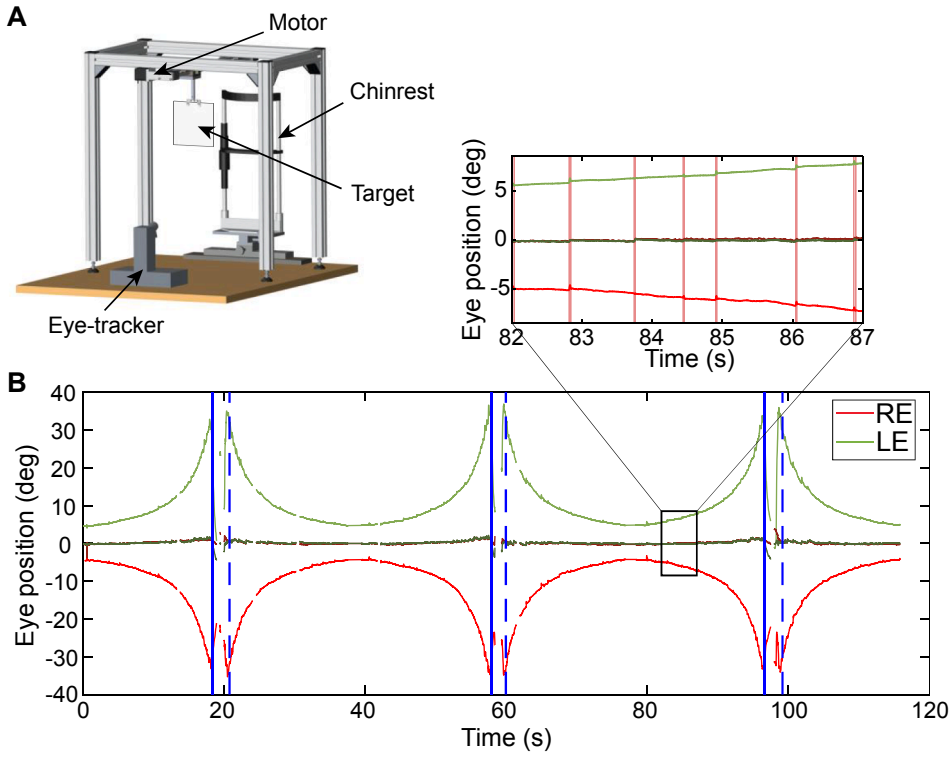

Fig. 1. (A) Schematic representation of the experimental setup. (B) Horizontal (light) and vertical (dark) positions of the right (red) and left (green) eyes of Subject 4 registered by EyeLink during the NPC test. The solid and dashed vertical blue lines represent the moment when the subject reported diplopia and recovery of single vision, respectively. The inset (above) shows an enlarged 5-second section of the eye-position record. In the inset, the red vertical lines represent saccades detected by an unsupervised clustering algorithm (Otero-Millan, Castro, Macknik, & Martinez-Conde, 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vergence response but have a functional purpose. As concurrent saccades have been shown to speed up vergence movements (Erkelens, Steinman et al., 1989), they might contribute to a strategy to bring one eye, perhaps the dominant eye, closer to the target in a shorter amount of time. As a result, the other eye would be moved transiently away from the target (Collewijn et al., 1995; Zee et al., 1992). Kenyon et al. (1980) concluded that despite the disconjugacy in amplitude, the saccades during vergence have normal dynamics, as they follow the saccadic main sequence.

Few studies have analyzed the characteristics of involuntary saccades during symmetrical vergence movements or during binocular fixation at different viewing distances, and none of them used ramp vergence stimuli. Krauskopf, Cornsweet, and Riggs (1960) found no consistent differences between saccades' features during binocular fixation at far (infinity) and near (55 cm) distances. However, these tested distances are not within the operational range of the NPC test and are far from the normal limits of convergence (Scheiman et al., 2003). The number of saccades exhibited during vergence movements in response to symmetrical vergence step stimuli has been found to be inversely correlated to the vergence peak velocity, i.e., when vergence peak velocity is slow, a greater number of saccades is observed (Kim & Alvarez, 2012). Convergence peak velocity has been found to be reduced in subjects with convergence insufficiency (Alvarez et al., 2010), who in that study had mean NPC break and recovery points of 13.4 cm and 20.8 cm, respectively. Consequently, these subjects also exhibited an increased prevalence of saccades during vergence responses, which has been thought to be a compensatory mechanism for challenged vergence dynamics (Alvarez & Kim, 2013; Zee et al., 1992). These findings lead to the plausible expectation that the characteristics of concurrent saccades during vergence may change as a function of the vergence demand and effort at different viewing distances, and to the hypothesis that some saccades' characteristics during the NPC test may serve as a surrogate indicator of the distance at which convergence breaks and/or recovers.

The main purpose of this study was to analyze the characteristics of small saccades that occur during NPC testing as a function of vergence demand. Specifically, we wondered whether saccadic features such as

amplitude, the peak-velocity-amplitude relationship (main sequence), directional conjugacy or frequency can be used as objective markers to predict NPC break and/or recovery points. The potential role of saccades in correcting fixation position and disparity errors during vergence also was investigated. To accomplish these goals, new methodological tools were developed to overcome the technical challenges of measuring eye movements over a span of viewing distances and vergence angles.

2. Materials and methods

2.1. Subjects

Eleven non-presbyopic adults participated in the study (mean age ± standard deviation (SD) of 25.4 ± 2.2 years). All subjects had 20/20 visual acuity or better in both eyes at distance and near with their habitual refractive correction. Spherical refractive errors ranged from −6.50 D to + 0.50 D with astigmatism up to −0.75 D. During the experiment, four subjects (subjects 2, 5, 6 and 10) wore spectacles and 2 subjects (subjects 7 and 9) wore contact lenses. All participants except subjects 2 and 10 had a NPC break point (assessed with a pen tip and averaged across 3 replications) equal to or closer than 5 cm and a recovery point closer than 7 cm. All except 2 of the participants had stereoacuity of 20 arc sec or better measured with the graded circle test of the Random Dot 2 Stereo Acuity Test with LEA Symbols (Vision Assessment Corp., Elk Grove Village, IL, USA). The two subjects with slightly receded NPCs had normal stereopsis. Refer to Table 1 for the detailed clinical characteristics of each participant.

The study was approved by the Ethics Committee of Hospital Mutua de Terrassa (Terrassa, Spain) and followed the tenets of the Declaration of Helsinki. All subjects gave informed written consent prior to participation in the study.

2.2. Instrument and visual stimulus

The fixation target was a crosshair consisting of a 2 × 2 mm cross surrounded by a 7 mm diameter circle. On the upper and bottom part of the circle there were two vertical lines with a length of 28 mm vertically aligned with the central cross. As a result, the cross subtended an angle of 0.29 deg and the whole stimulus subtended angles of 1 deg (width) and 5 deg (height) at 40 cm. An accommodative target was chosen to maximize the accommodative demand and stimulate accommodative convergence (Adler, Cregg, Viollier, & Woodhouse, 2007; Scheiman et al., 2003). The fixation target was black printed on white paper.

The visual stimulus was mounted on a track along which it could be moved forward and backward by a stepper motor (Fig. 1A). The motor was controlled by custom software coded in Matlab R2017a (MathWorks, Natick, MA, USA) and synchronized with an EyeLink 1000 Plus (SR Research Ltd., Ontario, Canada) to register binocular eye movements at a sampling rate of 500 Hz using the pupil ellipse fitting tracking mode. The EyeLink was positioned at its normal operating distance (around 50 cm) under the track and the target in order to record the eyes throughout the whole experiment.

2.3. Experimental procedure

Participants were positioned on a chinrest and aligned so that the central fixation cross and subjects' eyes lay on the same horizontal plane and the target moved along the midline to elicit symmetrical convergence and divergence movements.

First, the built-in 9-point EyeLink calibration was performed for each eye separately by asking the subjects to fixate on each of 9 circles that subtended an angle of 0.86 deg. Instead of using a monitor to display the calibration targets, the circles were printed on white paper and mounted on the track at a viewing distance of 40 cm. The eye-tracker was able to locate the pupil and detect the first Purkinje image for the whole range of convergence angles required during the NPC test. However, this span of angles is considerably wider than the linear tracking range of the eye-tracker according to manufacturer's specifications (32 deg horizontally). For that reason, a further custom dynamic calibration procedure was carried out. This procedure also contributed to minimize any potential effect on the measured eye positions of a pupil-size artefact caused by nonconcentric pupil miosis (Wildenmann & Schaeffel, 2013).

During the dynamic calibration, participants fixated separately with each eye on the same stimulus used later for the NPC testing while it moved from 40 cm to 2.8 cm along the midline at a constant velocity of 2 cm/s and back to 40 cm again. Participants were advised beforehand that they would perceive the target blurred at the closest distances. They were asked to maintain fixation on the center of the cross as precisely as possible. The complete calibration sequence in an experimental session was as follows: 9-point EyeLink calibration of the right eye and left eye, dynamic calibration of the right eye, and dynamic calibration of the left eye. Data collected during the dynamic calibration procedure were used to correct the horizontal gaze position measured for each eye during the NPC test offline. Full details on how these corrections were performed are provided in the following section.

The NPC test started immediately after the calibration procedures were completed. Subjects were asked to fixate binocularly on the central part of the cross of the crosshair, which was placed initially at 40 cm. After a random time between 1 and 3 s, the target started moving toward the subject at a constant velocity of 2 cm/s until it reached a viewing distance of 2.8 cm. Participants were asked to press a key on the keyboard when they perceived double vision. Regardless of the moment they reported diplopia, the target always reached the shortest distance. It remained at that position and after 1 s it moved backward to 40 cm at the same velocity. Participants were asked to press again a key when they recovered single binocular vision. As the linear velocity of the target was constant at 2 cm/s, vergence demand increased or decreased nonlinearly along the range of viewing distances. The total vergence demand during the test varied from about 8.6 deg at 40 cm to 93.9 deg at 2.8 cm. For the subjects who wore spectacles during the experiment, the prismatic effect produced by negative spherical lenses of −1.00 D to −3.50 D reduced the maximum required vergence by approximately 1.5 deg to 5.2 deg. The exact angles were slightly different across subjects depending on their interpupillary distance. This range of viewing distances was chosen to cover the distances typically used clinically to evaluate the NPC (Scheiman & Wick, 2014, p. 43). The closest distance (2.8 cm) was chosen to be very close to the subject while not touching the nose. This procedure was repeated three times consecutively, during which the EyeLink recorded the positions of both eyes at a sampling rate of 500 Hz.

2.4. Eye movement data analysis

Eye position data were processed offline using Matlab R2018a. Periods of 200 ms of the signal before and after each blink identified by the EyeLink software were removed to avoid artifacts associated with the onset and offset of blinks.

The EyeLink's HREF coordinate system was used to register eye position data following the recommendation of the manufacturer's support team (personal communication, September 18, 2017). Then, horizontal and vertical data were converted from HREF coordinates to degrees of visual angle as

$$eye_x = \left(\frac{HREF_x}{f} + \tan^{-1}\frac{IPD}{2{\cdot}calDist}\right){\cdot}\frac{180}{\pi} \quad (1)$$

$$eye_y = -\frac{HREF_y}{f}{\cdot}\frac{180}{\pi} \quad (2)$$

where eye_x and eye_y are the horizontal and vertical eye positions in degrees, respectively; $HREF_x$ and $HREF_y$ are the raw horizontal and vertical HREF coordinates, respectively; IPD is the interpupillary dis-

Table 2
Subjective break and recovery points averaged across the three repetitions of the NPC test ± SD for all subjects, and mean saccade rates ± SD (number of saccades per second) during the three convergence and divergence periods and separately as a function of vergence direction. Subjects 8 and 11 did not report diplopia during the NPC test and could fuse the stimulus up to the nose.

Subject	Break point (cm)	Recovery point (cm)	Saccade rate (Hz)		
			Convergence	Divergence	Overall
1	3.9 ± 0.4	5.2 ± 0.2	0.28 ± 0.32	0.27 ± 0.07	0.27 ± 0.16
2	5.9 ± 0.9	7.2 ± 0.2	1.76 ± 0.26	1.27 ± 0.46	1.52 ± 0.29
3	3.4 ± 0.5	5.0 ± 0.4	1.27 ± 0.17	1.29 ± 0.41	1.28 ± 0.27
4	3.9 ± 0.3	4.9 ± 0.3	1.42 ± 0.32	0.97 ± 0.06	1.19 ± 0.18
5	3.5 ± 0.7	5.6 ± 0.2	1.46 ± 0.14	1.67 ± 0.07	1.56 ± 0.05
6	4.8 ± 0.1	7.3 ± 0.8	1.44 ± 0.48	1.33 ± 0.12	1.38 ± 0.29
7	3.0 ± 0	6.9 ± 1.1	1.12 ± 0.26	0.81 ± 0.12	0.97 ± 0.18
8	–	–	1.63 ± 0.09	1.89 ± 0.26	1.76 ± 0.09
9	3.0 ± 0	4.3 ± 0.7	1.06 ± 0.17	1.08 ± 0.30	1.07 ± 0.19
10	3.0 ± 0	6.7 ± 2.1	3.05 ± 0.57	2.78 ± 0.90	2.92 ± 0.70
11	–	–	0.85 ± 0.26	0.74 ± 0.30	0.80 ± 0.08

tance measured with a pupillary distance ruler; *calDist* is the calibration distance (40 cm); and f is a constant with a value of 15000. The EyeLink's intrinsic heuristic filter was switched off during the registration of eye position. Then, the data were filtered offline with a third order Savitzky-Golay filter of 11 samples length (22 ms) (Savitzky & Golay, 1964).

A fourth order polynomial equation was adjusted by least-squares fitting to the curve defined by the actual target position and the horizontal eye position during the periods of the dynamic calibration when the target was approaching and receding computed with Eq. (1). The coefficients of the fitted polynomial were then applied to the horizontal data registered during the NPC test to compensate for the potential nonlinearity of the eye-tracker at large convergence angles. The signals from each eye were calibrated separately with the dynamic calibration coefficients of the corresponding eye.

Although the target did not move vertically, some subjects exhibited variations in their vertical eye position with the target distance. In some cases, this resulted in changes in vertical vergence which were thought to be due to system noise (Bedell & Stevenson, 2013) or a vertical misalignment between the heights of the two eyes. Even a small linear difference in vertical position would result in a considerable angular error that would increase at shorter fixation distances. The vertical eye-position traces computed with Eq. (2) were corrected to overcome this error (see Appendix A for details).

Saccades were detected with an unsupervised clustering method (Otero-Millan, Castro, et al., 2014). A few changes were incorporated to adapt the online version of this algorithm to our data. This included removing the constraint of ignoring a 1-second period at the beginning of each trial, and correcting an apparent error in the implementation of the published version of the algorithm in which the direction of the right eye during binocular saccades was computed using the horizontal position of the left eye. The velocity-threshold-based algorithm proposed by Engbert and Kliegl (2003) and modified subsequently by Engbert and Mergenthaler (2006) with $\lambda = 6$ and a minimum duration of 6 ms also was used to identify saccades. The Engbert-Kliegl algorithm relies on the fact that the mean horizontal and vertical velocities during fixation are zero (Engbert & Kliegl, 2003). Thus, the algorithm was modified to fit our data, in which the mean eye horizontal velocity is not zero due to the movement of the fixation target (see Appendix A). Two detected saccades separated by <20 ms were fused into a single movement. A minimum intersaccadic interval of 20 ms also was imposed by the Otero-Millan algorithm. The performance of both the Otero-Millan and Engbert-Kliegl algorithms was checked by visual inspection of the traces. The Results section, below, reports the results from the unsupervised clustering method while the results obtained with the velocity-threshold-based algorithm are shown in Appendix B.

2.5. Statistical analysis

Statistical analysis was performed using SPSS Statistics 24 (IBM Corp., Armonk, NY, USA). The significance level was set at 0.05. Parametric tests were used with normally distributed variables while non-parametric tests were used when the variables were not distributed normally according to the *Shapiro-Wilk test*.

Saccades detected during the periods when the target was fixed at 40 cm or 2.8 cm were not included in the analysis, except to compute the evolution of saccade rate over time. *Spearman's rank-order correlation* was used to determine the strength of the associations between the saccade amplitude, peak velocity (main sequence) and vergence demand, and the correlations between the break and recovery points of the NPC with the mean saccade rate and the rate of directionally non-conjugate saccades. The *Mann-Whitney test* was used to analyze whether the distributions of saccade amplitude and directional differences between the two eyes differed as a function of the direction of the concurrent vergence movement (convergence vs divergence). The *Kruskal-Wallis test* was used to assess the effect of the saccades' direction (horizontal vs vertical vs oblique) on the differences in the direction of the two eyes. The *paired t-test* was used to assess the differences in mean saccade rate as a function of the direction of the vergence movement, and between the number of corrective and non-corrective (error-producing) saccades.

RStudio (Boston, MA, USA) and R's Circular Package (Agostinelli & Lund, 2017) were used to apply circular statistical tests in order to analyze the saccade direction data. Watson's test was used to determine whether the directions of saccades were uniformly distributed. Fisher's nonparametric test was used to analyze the differences in saccade direction as a function of the direction of the vergence movement.

3. Results

Participants' break and recovery points based on their reports of diplopia and fusion during the NPC test performed on the experimental bench are shown in Table 2. Two subjects did not report diplopia during the test. The mean differences in the break and recovery points between the three repetitions were not clinically relevant, nor were the mean differences between the break and recovery points measured with the pen tip (see Table 1) and on the experimental bench (<0.5 cm). The reported mean ± SD accuracy of the EyeLink's calibration at 40 cm was 0.33 ± 0.11 deg averaged across eyes and participants. All subjects exhibited saccades during the vergence movements (Table 2). An example of eye traces registered by EyeLink during the NPC test can be seen in Fig. 1B.

A total of 1554 saccades with a median amplitude of 0.48 deg (range from 0.12 to 12.26 deg) were detected in the periods when the fixation target moved forward and backward. Most of the saccades (83.6%) had an amplitude smaller than 1 deg. Saccades during convergence and divergence followed the main sequence ($R_s = 0.95$, $p < 0.001$) as shown in Fig. 2A.

Saccade amplitude increased significantly with vergence demand ($R_S = 0.60$, $p < 0.001$) (Fig. 2, A and B panels). All individual subjects showed a significant positive correlation with coefficients ranging from 0.55 to 0.85 (all values of $p \leq 0.001$). We considered whether the increase in saccadic amplitude at the nearest target distances might reflect

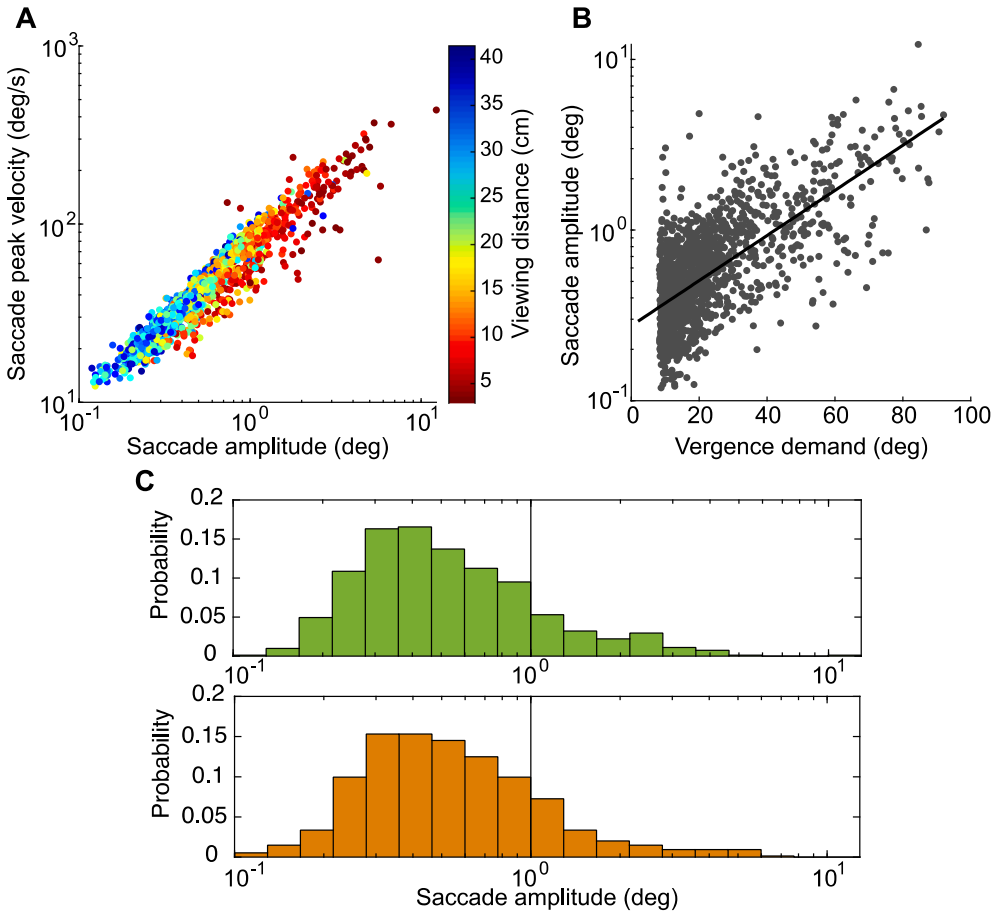

Fig. 2. (A) Main sequence on a log–log scale as a function of the viewing distance. The color code exposes the tendency for greater saccade amplitudes and peak velocities at shorter viewing distances. (B) Saccade amplitude as a function of vergence demand. The black line corresponds to the least-squares regression fit, which is shown only for illustrative purposes (Pearson $R^2 = 0.48$). (C) Amplitude distribution of saccades detected during convergence (top) and divergence (bottom) periods. The black vertical lines at amplitude = 10^0 deg show that most saccades had an amplitude smaller than 1 deg and can therefore be presumably considered to be equivalent to fixational microsaccades in terms of size, even though the fixation target in our experiment was not stationary.

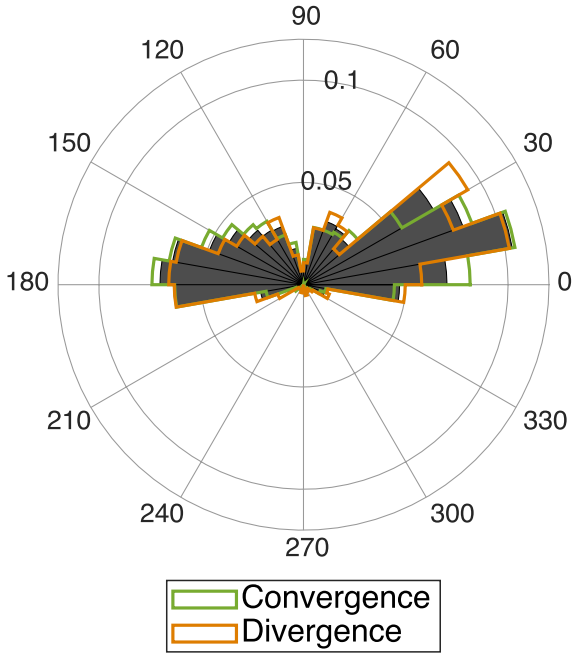

Fig. 3. Polar histogram of the saccade directions (gray sectors). The directions of saccades during convergence and divergence periods are shown with green and orange lines, respectively. Zero and 90 degrees indicate rightward and upward saccades, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

back-and-forth saccades after fusion was lost between the two images of the target. However, inspection of the eye position traces during the periods that the subjects reported diplopia revealed no instances in which fixation alternated between the two unfused images. There was no significant effect of the direction of the vergence movement on the amplitude of saccades according to the Mann-Whitney test ($p = 0.224$) (Fig. 2C).

The distribution of saccade directions is shown in Fig. 3. The directions of saccades differed significantly from a uniform distribution as shown by Watson's test for circular uniformity ($p < 0.01$). A higher prevalence of horizontal than vertical saccades was found, with more upwards than downwards vertical components. According to Fisher's nonparametric test for common median directions, the median direction of saccades during convergence (70.80 deg) and divergence (63.28 deg) did not differ significantly ($p = 0.542$).

Both horizontal (directions of ± 22.5 deg from horizontal) and vertical (directions of ± 22.5 deg from vertical) saccades exhibited the same trend as all saccades to increase in amplitude with vergence demand (horizontal: $R_S = 0.62$, $p < 0.001$; vertical: $R_S = 0.56$, $p < 0.001$). All individual subjects except one (Subject 7) showed a significant positive correlation between the amplitude of horizontal saccades and the horizontal vergence demand with correlation coefficients ranging from 0.54 to 0.86 (all values of $p \leq 0.008$). Higher inter-subject variability was found for vertical saccades. Only the three participants who made more than a total of 25 vertical saccades (subjects 3, 7 and 11) showed a significant correlation between saccade amplitude and the horizontal vergence demand.

The difference in saccade direction between the two eyes is shown in Fig. 4A. In 193 saccades (12.4%) the direction of the two eyes was found to differ by more than ± 45 deg, and in 109 (7.0%) the difference was greater than ± 90 deg. The individual observers' proportions of

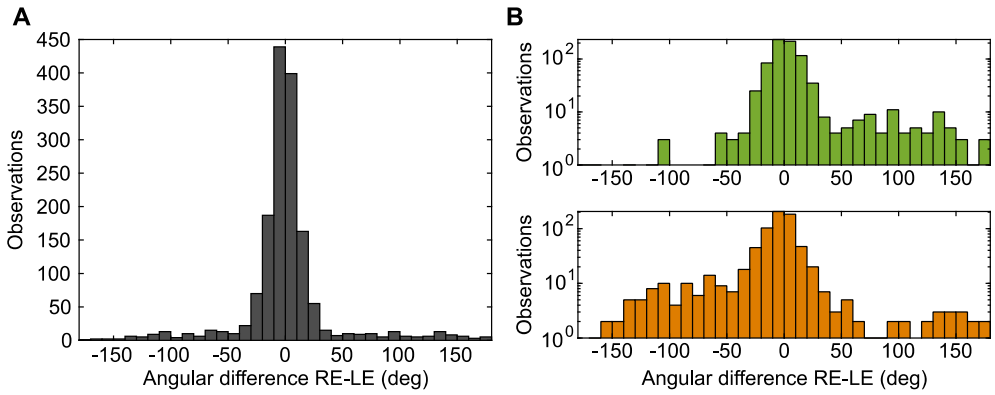

Fig. 4. (A) Histogram of the angular difference in saccade direction between the two eyes (direction of the right eye minus direction of the left eye) in degrees. An angular difference of 0 deg means that the two eyes moved in the same direction, whereas ± 180 deg means that the saccade had opposite directions in the two eyes. (B) Histograms of the between-eye differences in saccade direction during convergence (top) and divergence (bottom). Note that the vertical axes are scaled logarithmically in panel (B) to emphasize the numbers of saccades that differed in direction in the two eyes.

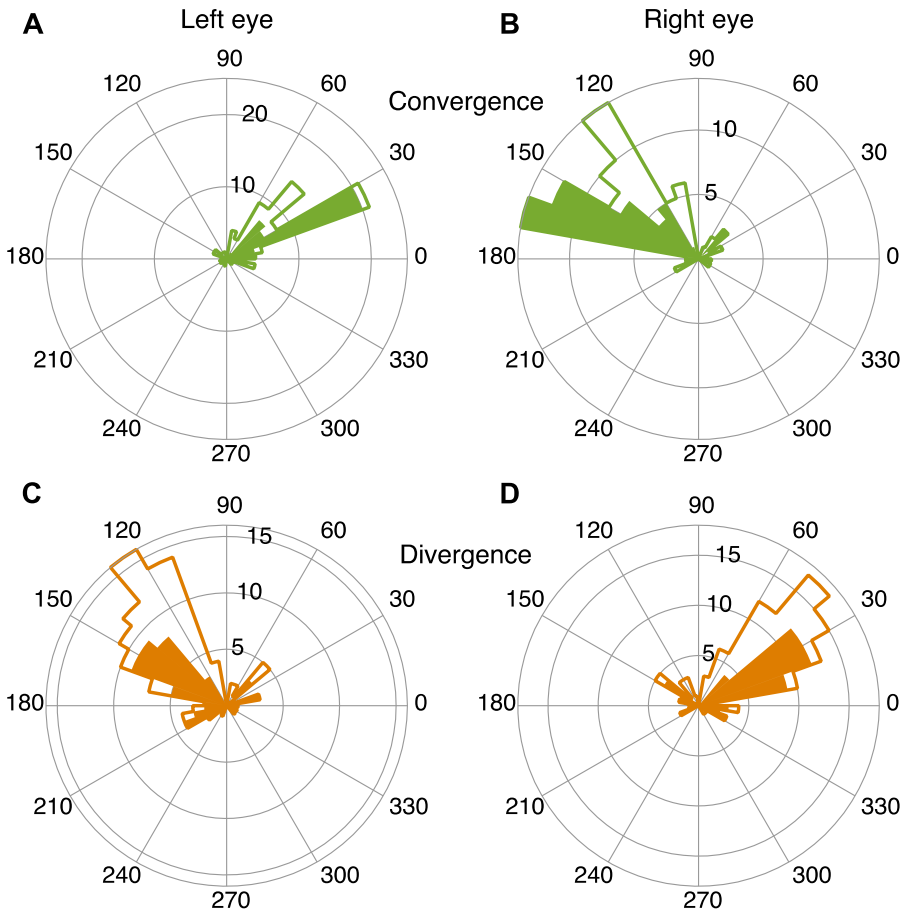

Fig. 5. Distribution of the right (panels (B) and (D)) and left (panels (A) and (C)) eyes' directions for the directionally non-conjugate saccades as a function of the direction of the concurrent vergence movement (convergence: panels (A) and (B); divergence: panels (C) and (D)). The unfilled distributions limited by the solid lines are the directions of saccades which differed in the two eyes by more than ± 45 deg, while the areas shaded in color represent the directions of saccades which differed in the two eyes by more than ± 90 deg.

directionally non-conjugate saccades did not show a significant correlation with the results of the NPC test (break: R_S = 0.29, p = 0.447; recovery: R_S = -0.32, p = 0.410). Overall, the occurrence of directionally non-conjugate saccades was similar during the periods of convergence and divergence. However, the distribution of the directional differences was significantly different depending on the direction of vergence according to the Mann-Whitney test ($p < 0.001$) (Fig. 4B). The long tails towards positive angular differences during convergence and toward negative differences during divergence indicate that the direction of the right eye movement tended to be more leftward than the direction of the left eye during convergence and more rightward during divergence. This behavior is illustrated further in Fig. 5, in which the directions of the right and left eyes during the directionally non-conjugate saccades are represented as a function of the direction of the concurrent vergence movement.

The medians (interquartile range; IQR) of the directional differences were similar for horizontal, vertical and oblique saccades: 0.28 deg (12.74 deg) for horizontal saccades, −6.72 deg (31.24 deg) for vertical saccades, and −2.07 deg (24.67 deg) for oblique saccades. Nevertheless, the distributions of the directional differences between the eyes differed significantly as a function of the direction of the saccades as shown by the Kruskal-Wallis test ($p < 0.001$). Specifically, the distribution of the directional differences between the eyes of horizontal saccades differed significantly from that of vertical and oblique saccades ($p < 0.001$). No significant differences were found between vertical and oblique saccades ($p = 0.316$).

The saccade rate averaged across subjects and the three repetitions was 1.34 ± 0.66 Hz. There were weak non-significant correlations

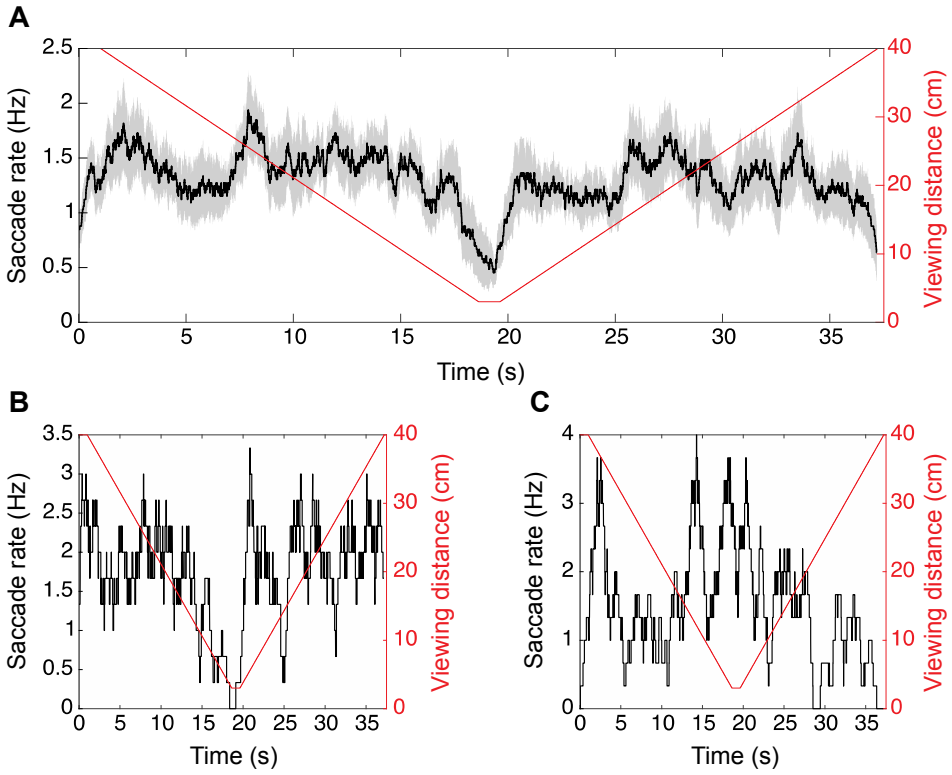

Fig. 6. (A) Saccade rate over time averaged across subjects and the three repetitions (black line). The shaded area corresponds to ± 1 standard error of the mean (SEM). The right axis and the red line represent the target distance. (B) Saccade rate over time averaged across the three repetitions for a representative subject (Subject 8) who showed a decreased saccade rate at the closest target distance (black line). The right axis and the red line represent the target distance. This participant did not report diplopia during any of the three repetitions of the test. (C) Saccade rate over time averaged across the three repetitions for a second representative subject (Subject 2), who showed an increased saccade rate at the closest target distance (black line). The right axis and the red line represent the target distance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Number of saccades that corrected or produced a horizontal disparity error; number of saccades that brought the right eye (RE) or the left eye (LE) closer to the target; and the dominant eye of each subject.

Subject	Disparity correcting saccades	Disparity inducing saccades	Saccades correcting RE fixation position	Saccades correcting LE fixation position	Dominant eye
1	16	13	13	17	RE
2	86	74	81	**94**	LE (1st and 2nd rep); RE (3rd rep)
3	100	35	46	**103**	LE
4	57	69	**70**	35	RE
5	107	58	59	**65**	LE
6	106	40	**89**	58	RE
7	55	47	**58**	48	RE
8	129	57	80	107	–
9	57	56	43	**54**	LE
10	176	132	**170**	135	RE
11	38	46	28	52	–

rep: repetition.

between the mean saccade rate and the break ($R_S = 0.11$, $p = 0.777$) and recovery ($R_S = 0.38$, $p = 0.308$) points of the NPC test. Overall, the mean saccade rate during convergence (1.39 ± 0.68 Hz) and divergence (1.28 ± 0.67 Hz) did not differ significantly [t(10) = 1.53, $p = 0.158$]. Saccade rates of each individual participant are reported in Table 2. The evolution of saccade rate over time was computed by using a moving window of 1 s. On average, saccade rate decreased to around 0.5 Hz at the closest target distance (Fig. 6A). However, the prevalence of saccades during vergence movements was idiosyncratic. Whereas five participants showed a decreased saccade rate with higher vergence demand (Fig. 6B), two subjects showed the opposite behavior and made more saccades at the closest target distance (Fig. 6C). The other four subjects showed no clear trend to change saccade rate with vergence demand.

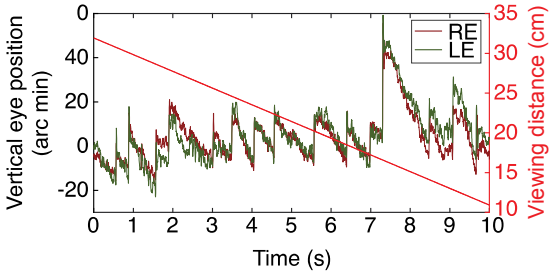

Fig. 7. Vertical position traces of the right and left eyes of one of the six observers (Subject 5) who exhibited a small upbeating vertical nystagmus (slow downward drift interrupted by upward saccades). Positive and negative values indicate upward and downward movements, respectively. The right axis and the red straight line represent the target distance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Overall, the number of saccades that reduced a horizontal vergence error (disparity) exceeded significantly the number of error-producing saccades [t(10) = 2.81, $p = 0.018$] (Table 3). The convergent and divergent components of saccades are illustrated in Fig. 4 and emphasized in Fig. 5 for directionally non-conjugate saccades. All subjects except two (Subjects 4 and 11) made more disparity-correcting saccades than disparity-inducing saccades. Considering the horizontal fixation position error of each eye separately, for most subjects saccades tended either to move one eye closer to the target and the other eye either farther from the target or produced no change. The number of saccades of each subject in which the right and left eyes moved closer to the target is shown in Table 3. For all subjects except Subject 1, the eye with more corrective saccades corresponded to the dominant eye (see the numbers in bold in Table 3). The eye dominance was determined by visually inspecting the ocular traces as the eye that either maintained fixation or deviated less after fusion loss, or the eye that made the initial recovery movement in the correct direction (Coren & Kaplan, 1973; Porac &

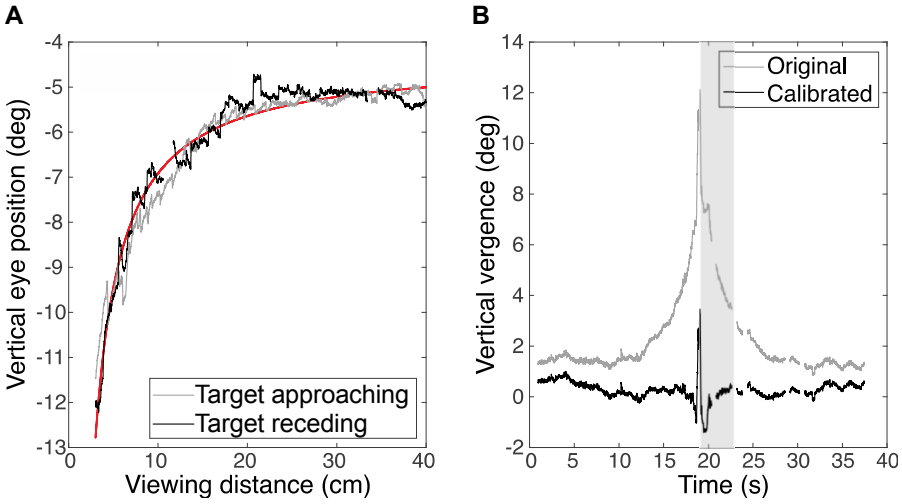

Fig. A1. (A) Vertical right eye position of Subject 10 during the target-approaching (gray line) and target-receding (black line) periods during dynamic calibration as a function of the viewing distance. The red line corresponds to the fitted function according to Eq (A.1) (a = −0.44 cm, b = −4.4 deg, R^2 = 0.96). (B) Vertical vergence exhibited by the same subject during the first repetition of the NPC test before (gray line) and after (black line) correction of the vertical traces. The shaded area corresponds to the period when the subject reported diplopia. The large spike in the two vertical vergence traces before time = 20 s might be an artifact associated with the loss of fusion.

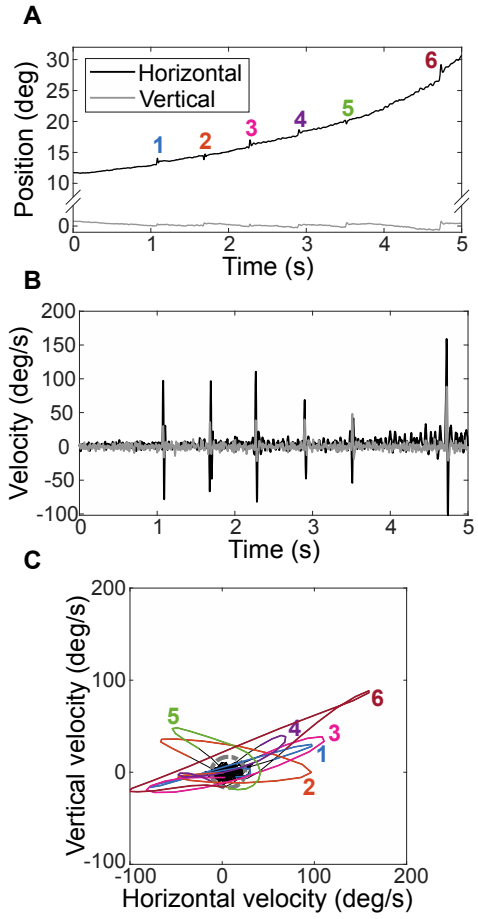

Fig. A2. (A) Horizontal (black) and vertical (gray) eye position of Subject 5 during a 5-second period of the NPC test. During this period the observer exhibited six saccades, which are identified with numbers. (B) Horizontal (black) and vertical (gray) components of eye velocity during the same period of the NPC test. (C) Plot of the trajectory in velocity space. The ellipse used as the criterion to identify saccades is represented in gray. Its horizontal and vertical center is at 6.60 and 0 deg/s, respectively. The six saccades showed considerably higher velocities than the median velocity during the 5-second period.

Table B1
Mean saccade rate ± SD (number of saccades per second) exhibited during the three convergence and divergence periods and separately as a function of vergence direction.

Subject	Saccade rate (Hz)		
	Convergence	Divergence	Overall
1	0.34 ± 0.28	0.30 ± 0.03	0.32 ± 0.14
2	1.89 ± 0.34	1.36 ± 0.44	1.63 ± 0.26
3	1.31 ± 0.15	1.36 ± 0.37	1.33 ± 0.22
4	1.33 ± 0.17	0.95 ± 0.09	1.14 ± 0.08
5	1.61 ± 0.12	1.72 ± 0.14	1.67 ± 0.09
6	1.46 ± 0.43	1.40 ± 0.13	1.43 ± 0.27
7	1.33 ± 0.29	0.91 ± 0.06	1.12 ± 0.16
8	1.70 ± 0.06	2.01 ± 0.27	1.86 ± 0.11
9	1.21 ± 0.12	1.21 ± 0.12	1.21 ± 0.06
10	2.97 ± 0.43	3.09 ± 0.95	3.03 ± 0.67
11	0.85 ± 0.26	0.72 ± 0.27	0.79 ± 0.07

Coren, 1976; Von Noorden & Campos, p. 207, 2002). This method to assess *motor* eye dominance has been found to exhibit high repeatability and moderate agreement with various *sighting* ocular dominance tests (Li et al., 2010; Rice, Leske, Smestad, & Holmes, 2008). The dominant eye of subjects 8 and 11 could not be determined as these participants did not lose fusion during the NPC test.

Overall, 56% of the saccades corrected the fixation position of the dominant eye, while 41% contributed to reduce the fixation position error of the non-dominant eye. In 4 participants, the median error induced in the non-dominant eye was smaller than the median error corrected by the dominant eye, which was up to 0.13 deg. Two participants showed the opposite behavior. In 2 other subjects, saccades induced a small fixation error in both eyes, although it was smaller in the dominant eye.

4. Discussion

All participants made a considerable number of saccades while they tracked a target moving in depth to test the NPC. Their saccades followed the main sequence with a similar slope to that reported for visually-guided saccades (Bahill, Clark, & Stark, 1975; Coubard & Kapoula, 2008) and saccades that occurred during vergence (Coubard & Kapoula, 2008; Kenyon et al., 1980), and slightly lower but still comparable to that for fixational microsaccades (Galfano, Betta, & Turatto, 2004; Zuber, Stark, & Cook, 1965).

Saccade amplitude increased and, on average, rate decreased with vergence demand. One might hypothesize that these effects could be

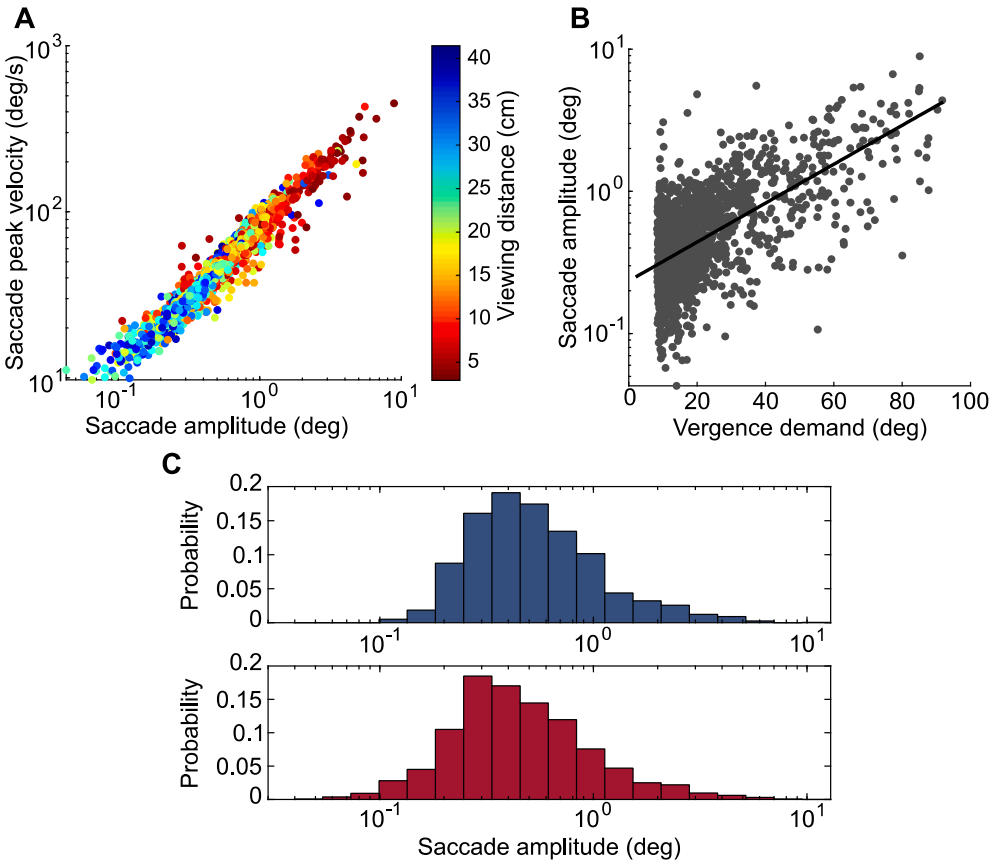

Fig. B1. (A) Main sequence on log–log scale as a function of the viewing distance. The color code exposes the tendency for greater saccade amplitude and peak velocity at shorter viewing distances. (B) Saccade amplitude as a function of vergence demand. The black line corresponds to the least-squares regression fit, which is shown only for illustrative purposes (Pearson $R^2 = 0.40$). (C) Amplitude distribution of saccades detected with the clustering method (top) and with the modified version of the E-K algorithm (bottom).

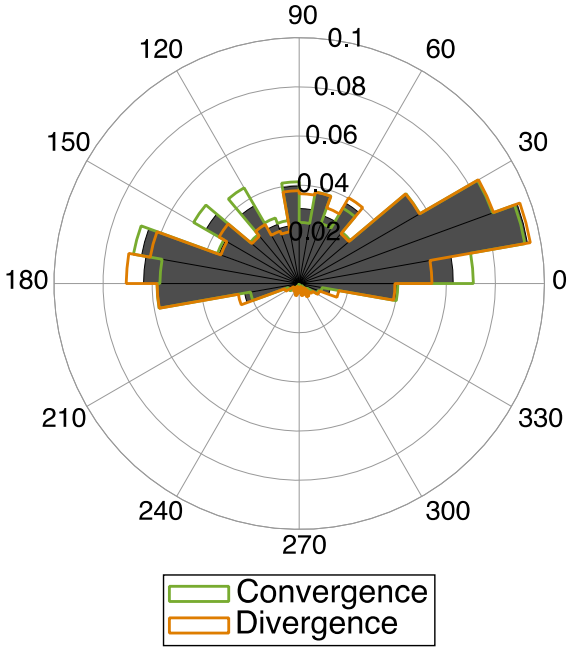

Fig. B2. Polar histogram of the saccade directions (gray sectors). The direction of saccades during convergence and divergence periods is shown with green and orange lines, respectively. Zero and 90 degrees indicate rightward and upward saccades, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

explained by the increased effort of the vergence system to maintain fusion at short viewing distances, which would be consistent with previous findings that considered saccades during vergence as a compensation for slow vergence dynamics (Alvarez & Kim, 2013; Erkelens, Steinman et al., 1989; Kim & Alvarez, 2012; Zee et al., 1992). If that would be the case, saccade amplitude and frequency could be used as objective markers to predict the break and recovery points of the NPC test, with the potential to be translated into a new, automated and accurate method to assess the NPC in clinic. However, our results show only a weak correlation between the participants' mean saccade rate and the break and recovery points of the NPC, and the evolution of saccade rate over time was idiosyncratic. These observations lead to the conclusion that these saccade parameters are not an accurate indicator of fusion loss.

Alternatively, the observed changes in saccadic amplitude and rate might be explained by the more rapid change of vergence demand and the greater angular size of the fixation target at near than at far (McCamy, Najafian Jazi, Otero-Millan, Macknik, & Martinez-Conde, 2013; Steinman, 1965). Because our intent was to mimic clinical procedures used to assess the NPC, the fixation target had a constant physical size. Therefore, while the central fixation cross subtended an angle of 0.29 deg at 40 cm, its angular size increased nonlinearly up to 4.1 deg at 2.8 cm. The accommodation limit and the blurred perception of the fixation target at close distance might also lead to greater saccade amplitudes (Ghasia & Shaikh, 2015). Further research using targets with constant angular size moving at constant angular velocity might be useful to disentangle the effect of target characteristics such as blur, size and velocity from the effect strictly related to the effort of the vergence system. While the current study establishes a baseline for the normative characteristics of saccades during the NPC test for typical adult subjects, other studies using subjects with a receded NPC such as those with convergence insufficiency would be helpful to determine potential differences in these saccadic characteristics. We hypothesize that subjects

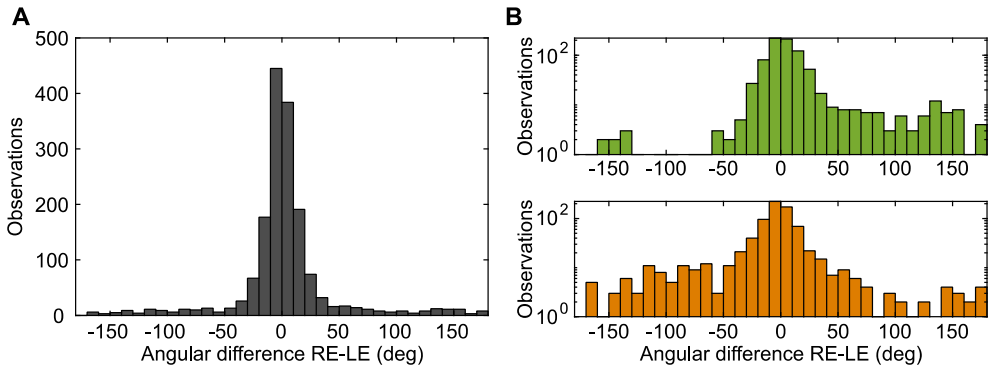

Fig. B3. (A) Histogram of the angular difference in saccade direction between the two eyes (direction of the right eye minus direction of the left eye) in degrees. An angular difference of 0 deg means that the two eyes moved in the same direction, whereas ± 180 deg means that the saccade had opposite directions in the two eyes. (B) Histograms of the between-eye differences in saccade direction during convergence (top) and divergence (bottom). Note that the vertical axes are scaled logarithmically in panel (B) to emphasize the numbers of saccades that differed in direction in the two eyes.

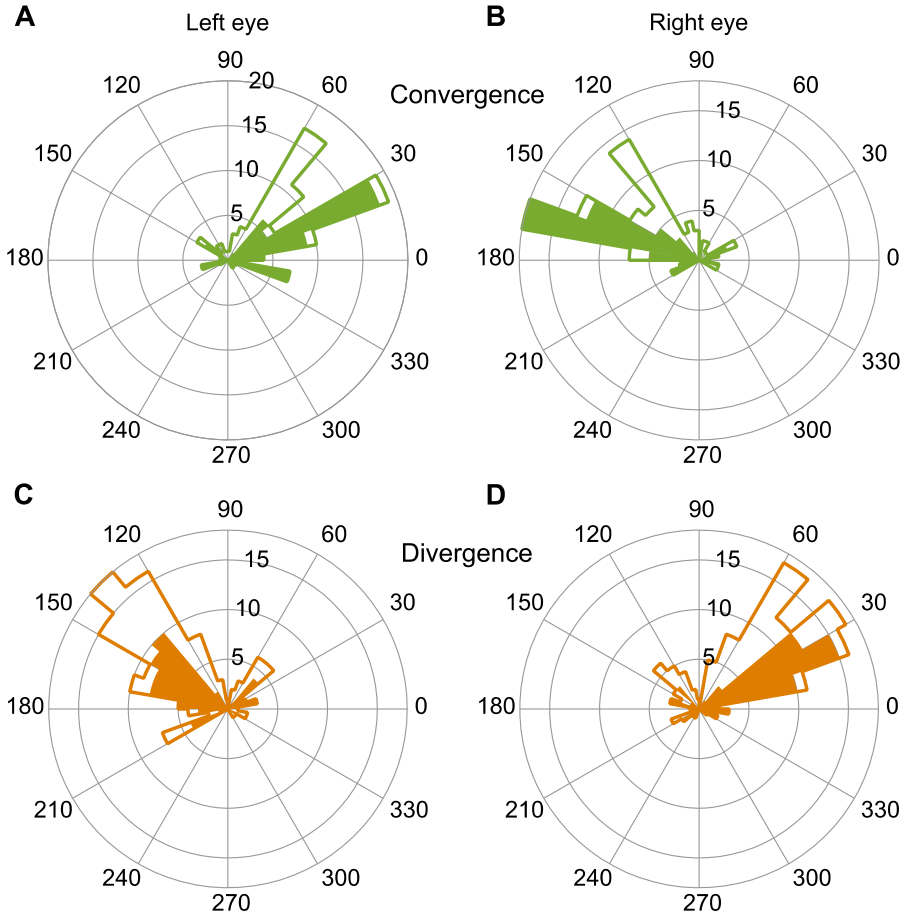

Fig. B4. Distribution of the right (panels (B) and (D)) and left (panels (A) and (C)) eyes directions for the directionally non-conjugate saccades as a function of the direction of the concurrent vergence movement (convergence: panels (A) and (B); divergence: panels (C) and (D)). The unfilled distributions limited by the solid lines are the directions of saccades which differed in the two eyes by more than ± 45 deg, while the areas shaded in color represent the directions of saccades which differed in the two eyes by more than ± 90 deg.

with convergence insufficiency may exhibit a larger number of saccades during the NPC test in an attempt to overcome their limited convergence ability. Even if saccade rate or the amplitude distribution at the break or recovery points is not enough to predict the outcome of the NPC test, a general difference in these characteristics could allow clinicians to readily identify patients with binocular dysfunction in an objective and more accurate and precise manner. Similarly, the objective measurement of saccade characteristics could represent a tool to monitor objectively the effect of vision therapy, or other treatments, in patients with binocular and/or accommodative disorders. Further research is needed to identify any saccade-related signs of these disorders and determine normative values.

In agreement with the reported distributions of fixational microsaccades, saccades detected during vergence movements showed a preference for horizontal directions (Abadi & Gowen, 2004; Engbert, 2006; Nyström, Andersson, Niehorster, & Hooge, 2017). However, vertical and oblique saccades were not observed as exceptionally as previously reported. The bias in vertical saccadic components in the upwards direction cannot be explained by a potential movement of the target in the vertical plane because the saccade direction did not reverse between convergence and divergence periods (Fig. 3). Instead, the high prevalence of upward saccades might reflect the tendency of some normal subjects to exhibit a small *upbeating vertical nystagmus* (Fig. 7). Six participants showed this behavior during the experiment. Stevenson, Sheehy, and Roorda (2016) previously reported this pattern of eye movement in the fixation of some normal observers, as registered using a binocular Scanning Laser Ophthalmoscope. The amplitude of vertical nystagmus also increased significantly with vergence demand as shown by the significant positive correlation between the amplitude of vertical saccades and vergence demand.

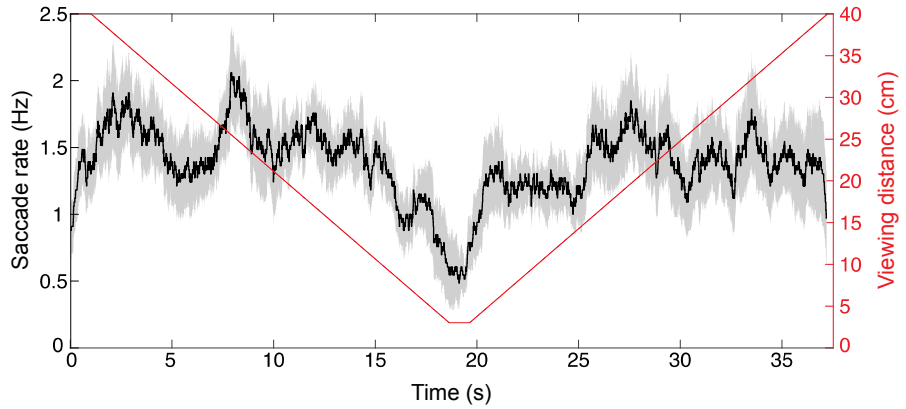

Fig. B5. Saccade rate over time averaged across subjects and the three repetitions (black line). The shaded area corresponds to ± 1 standard error of the mean (SEM). The right axis and the red line represent the target distance.

Table B2
Number of saccades that corrected or produced a horizontal disparity error; number of saccades that brought the right eye (RE) or the left eye (LE) closer to the target; and the dominant eye of each subject.

Subject	Disparity correcting saccades	Disparity inducing saccades	Saccades correcting RE fixation position	Saccades correcting LE fixation position	Dominant eye
1	19	15	14	19	RE
2	86	86	83	**87**	LE (1st and 2nd rep); RE (3rd rep)
3	85	56	47	**103**	LE
4	53	67	**58**	31	RE
5	116	60	60	**68**	LE
6	108	43	**97**	60	RE
7	68	50	**65**	55	RE
8	85	111	79	107	–
9	80	48	59	**62**	LE
10	185	135	**180**	134	RE
11	42	41	32	52	–

rep: repetition.

Saccades performed during vergence movements are not perfectly conjugated (Erkelens, Steinman et al., 1989; Kenyon et al., 1980). As suggested by some authors (Erkelens, Steinman et al., 1989; Kenyon et al., 1980; Ono & Nakamizo, 1978; Ono, Nakamizo, & Steinbach, 1978; Zee et al., 1992), saccades with unequal amplitudes in the two eyes during vergence could result from the non-linear combination of independently generated vergence and saccadic commands at or before the level of oculomotor neurons. This interpretation, for which neurophysiological evidence has been found (Busettini & Mays, 2005; Kumar et al., 2006; Mays & Gamlin, 1995), is compatible with Hering's law of equal innervation (Hering, 1977). Other authors provided evidence that oculomotor commands are sent independently to each eye (King & Zhou, 2002; Van Horn, Sylvestre, & Cullen, 2008), which would support the hypothesis that disjunctive saccades represent a violation of Hering's law. For reviews on the binocular control of eye movements and saccade-vergence interactions see (Coubard, 2013; King, 2011). In the current study special emphasis was placed on directional disconjugacy. The percentage of saccades in which the direction of the two eyes differed more than 45 degrees agreed with other studies of fixational microsaccades (Møller, Laursen, Tygesen, & Sjølie, 2002; Nyström et al., 2017). Previously, Krauskopf et al. (1960) found a higher degree of conjugacy between the directions of the saccades made by the two eyes. In agreement with Møller et al. (2002), we found no difference between the median amplitudes of saccades in which the two eyes moved in the same vs. different (>45 deg) directions (0.48 vs. 0.46 deg). Hence, saccades with different directions in the two eyes cannot readily be attributed to either neural or instrument noise, which would be expected to exert an effect primarily on small-amplitude saccades. In general, the directionally non-conjugate saccades were mostly oblique rather than horizontal or vertical. According to the polar plots in Fig. 5, the direction of the vertical saccadic component of these non-conjugate saccades appeared to be similar in the two eyes and the main source of disconjugacy was horizontal, as convergent and divergent components were found. This association of vertical version and horizontal vergence movements was also found in the version-vergence nystagmus exhibited in response to optical flow on the ground plane (Yang, Zhu, Kim, & Hertle, 2007; Zhu, Hertle, & Yang, 2008). The occurrence of directionally non-conjugate saccades with convergent and divergent components supports other observations that vergence eye movements are not always slow (Leigh & Zee, 2015). The disjunctive component of directionally non-conjugate saccades was mostly in the correct direction to reduce vergence error as shown in Fig. 4 and Fig. 5. Therefore, although the observation of saccades in different directions appears to represent a violation of Hering's law, the direction distributions shown in Fig. 4 and Fig. 5 may be consistent with Hering's law if interactions between the neural signals for version and vergence are considered prior to the level of the final common pathway (Busettini & Mays, 2005; Zee et al., 1992). The occurrence of directionally non-conjugate saccades and their prevalence in convergence or divergence periods were idiosyncratic among subjects, in agreement with Erkelens, Steinman et al. (1989). In our study, the subjects with more receded NPCs did not tend to exhibit more directionally non-conjugate saccades, as shown by the lack of correlation between these two parameters. Further research with subjects with receded NPCs could determine whether these subjects exhibit an increased number of disjunctive saccades during NPC testing, serving perhaps as corrective catch-up saccades during vergence, analogous to the error-reducing saccades that occur during smooth pursuit eye movements.

The potential role of fixational eye movements in maintaining accurate binocular fixation has been a matter of study for several decades (Otero-Millan, Macknik, & Martinez-Conde, 2014). Our results indicate that 59.7% of all the saccades performed during the NPC test reduced horizontal vergence errors (Table 3). Overall, the median horizontal vergence errors compensated by saccades during the convergence and divergence periods was 0.8 min arc and 3.1 min arc, respectively. Although binocular disparity is not a stimulus for fixational microsaccades (Krauskopf et al., 1960; St Cyr & Fender, 1969), involuntary microsaccades during fixation of a stationary target have been also found to correct similar amounts of binocular disparity (Engbert & Kliegl, 2004). However, these authors also found a considerable percentage of error producing microsaccades. Our results reveal a preference of subjects to reduce the fixation position error of the dominant eye

at the expense of inducing (or at least not correcting) the fixation error of the other eye, as previously suggested by Zee et al. (1992).

The adaptability of video-based eye-trackers allows to measure eye movements in a wide range of situations such as during the performance of optometric tests, which can provide more detailed information about some clinical conditions (Bedell & Stevenson, 2013). However, these instruments also have some limitations. The pupil size artefact is of particular concern for this study. This is a limitation of video-based eye-trackers that estimate gaze position from the first Purkinje image and the center of the pupil and is caused by a shift of the pupil center with changes of pupil size (Wildenmann & Schaeffel, 2013). As a result, the eye-tracker may measure eye drifts when the eyes have not actually moved (Choe, Blake, & Lee, 2016; Drewes, Masson, & Montagnini, 2012; Wyatt, 2010). Rather than a systematic shift of the measured eye positions, the pupil size artefact is an idiosyncratic error with considerable differences between individuals (Hooge, Hessels, & Nyström, 2019; Wildenmann & Schaeffel, 2013). The luminance of the fixation target was similar at all viewing distances, but pupil size fluctuates in response to several other types of exogenous and endogenous stimuli, such as occurs during the near triad (i.e. pupil constriction associated with convergence and accommodation). Thus, our data might not be totally free from the pupil size artefact. The custom monocular dynamic calibration performed by all subjects before the measures aimed to minimize the pupil size artefact, as the pupils also constricted during this calibration process. This approach is in line with the proposal of Drewes et al. to perform calibrations at different pupil sizes (Drewes et al., 2012; Drewes, Zhu, Hu, & Hu, 2014) and allows for a different impact of the pupil size artefact between participants. Although we cannot rule out completely the presence of the pupil size artefact on our results, the fact that the detected and analyzed saccades were all well clustered around a main sequence with a comparable slope to previous reports (Coubard & Kapoula, 2008; Galfano et al., 2004) is evidence of the quality and validity of the recordings and detected saccades.

5. Conclusions

Eye movements during the performance of the NPC test were measured on a sample of young adults. Small saccades were detected objectively and analyzed as a function of the vergence demand. All observers made involuntary small saccades during the NPC test. Both the average saccade amplitude and rate changed with vergence demand. However, the increment in amplitude and decrease in rate might be explained by the greater angular size of the fixation target at near than at far, rather than by interactions between the saccadic and vergence systems. In general, the direction of the vergence movement had no significant effect on saccade characteristics. A small percentage of saccades was not conjugated as they contained convergent or divergent components. Most non-conjugate saccades tended to correct binocular disparity errors. Finally, in most participants the majority of saccades tended to correct the fixation position error of the dominant eye.

CRediT authorship contribution statement

Clara Mestre: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Harold E. Bedell:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing - review & editing. **Fernando Díaz-Doutón:** Funding acquisition, Project administration, Resources, Software, Writing - review & editing. **Jaume Pujol:** Funding acquisition, Project administration, Resources, Supervision, Writing - review & editing. **Josselin Gautier:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing - review & editing.

Acknowledgments

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Appendix A

Correction of vertical eye-position traces

If the two eyes of the observer were not exactly at the same height in the head, vertical vergence would be required to maintain binocular fixation at close fixation distances. The change in vertical eye position would be expected to be explained by the inverse tangent of the vertical misalignment between the eye and target heights divided by the viewing distance.

Fig. A.1-A shows an example of the change in vertical eye position during the dynamic calibration with viewing distance. The vertical traces of 8 participants showed a similar behavior during the NPC test. The function

$$vertical\ position = \tan^{-1}\left(\frac{a}{distance}\right) + b \tag{A.1}$$

was fitted to the dynamic calibration data, where a is the parameter indicative of the vertical misalignment, *distance* is the distance of the fixation target from the observer, and b is a constant vertical position error. The estimated vertical misalignment (a) ranged between 0.01 mm and 0.44 cm.

The vertical position of each eye during the NPC test was corrected separately by subtracting the model fitted to the dynamic calibration data in Eq. (A.1) from the raw measured vertical position. As a result, the abnormal increase in vertical vergence shown at close distance due to relative misalignment in the height of the two eyes was reduced substantially (Fig. A1-B).

Modification of the Engbert-Kliegl (E-K) algorithm

Engbert and Kliegl (2003) proposed a saccade detection algorithm based on a velocity threshold adapted to the level of noise in the data. Specifically, the algorithm uses a multiple of the standard deviation of the velocity distribution as the saccade-detection threshold. This threshold is computed separately for horizontal and vertical eye-movement components. Saccades are identified as "outliers" in velocity space, i.e., samples with a velocity that lies outside an ellipse whose horizontal and vertical radii are the velocity thresholds. Because the mean eye velocity during fixation is assumed to be effectively zero, the ellipse is centered at zero horizontal and vertical velocity.

However, the mean horizontal velocity during the NPC test cannot be assumed to be zero, as the fixation target moved forward and backward at a constant linear velocity. The horizontal angular velocity of the eyes actually increased at close target distances. Therefore, two sliding time windows of 5 s and 48 ms were used to divide the time series and apply the detection algorithm. The velocity threshold was computed during each 5-second period

similarly than in the original E-K algorithm. The center of the ellipses used to identify the saccades in velocity space was computed as the median eye velocity over the shorter (48-ms) time window (Fig. A2). The lengths of the sliding time windows were determined as the ones which detected saccades that clustered optimally around the main sequence.

Appendix B

In this section, the results with the modified E-K algorithm are shown.

A total of 1639 saccades were detected by the modified version of the velocity-threshold-based algorithm. The number of saccades per second exhibited by each subject is shown in Table B1. For all observers except two, more saccades were detected with the E-K algorithm than with the clustering method (see Table 2).

The median saccade amplitude was 0.42 deg (range from 0.04 deg to 8.90 deg). Saccades during convergence and divergence followed the main sequence ($R_S = 0.97, p < 0.001$) as shown in Fig. B1-A. Most of the saccades (86%) had an amplitude smaller than 1 deg. The amplitude distribution of saccades differed significantly between the two detection algorithms according to the Mann-Whitney test ($p < 0.001$) (Fig. B1-C).

A significant positive correlation between saccade amplitude and vergence demand was found ($R_S = 0.55, p < 0.001$) (Fig. B1, A and B panels). This association was showed by all individual subjects, with correlation coefficients ranging from 0.32 to 0.86 (all values of $p \leq 0.001$). Similarly as with the clustering method, there was no significant influence of the direction of the vergence movement on the amplitude of saccades, according to the Mann-Whitney test ($p = 0.212$).

The distribution of saccade directions is shown in Fig. B2. The directions of saccades differed significantly from a uniform distribution as shown by Watson's test for circular uniformity ($p < 0.01$). Similar to the saccades detected by the clustering algorithm, a higher prevalence of horizontal than vertical saccades was found, with more upwards than downwards vertical components. The median direction of saccades during convergence (78.50 deg) and divergence (72.54 deg) did not differ significantly ($p = 0.387$).

Both horizontal (directions of ± 22.5 deg from horizontal) and vertical (directions of ± 22.5 deg from vertical) saccades exhibited the same trend to increase in amplitude with vergence demand (horizontal: $R_S = 0.59$, $p < 0.001$; vertical: $R_S = 0.49$, $p < 0.001$). All individual subjects except one showed a significant positive correlation between the amplitude of horizontal saccades and vergence demand with correlation coefficients ranging from 0.42 to 0.86 (all values of $p \leq 0.04$). Higher inter-subject variability was found for vertical saccades. All participants except four showed a significant correlation between vertical saccade amplitude and vergence demand, with correlation coefficients in the seven other participants ranging from 0.53 to 0.91 ($p \leq 0.03$).

The difference in saccade direction between the two eyes is shown in Fig. B3-A. In general, the number of directionally non-conjugate saccades is similar to that detected by the clustering algorithm. In 230 saccades (14.0%), the direction of the two eyes was found to differ more than ± 45 deg, and in 124 (7.6%) the difference was greater than ± 90 deg. Overall, the occurrence of directionally non-conjugate saccades was similar during the periods of convergence and divergence. However, the distribution of the directional differences was significantly different as a function of the direction of vergence according to the Mann-Whitney test ($p < 0.001$) (Fig. B3-B). The directions of the right and left eyes during the directionally non-conjugate saccades are represented as a function of the direction of the concurrent vergence movement in Fig. B4.

The median (IQR) of the directional differences between saccades was similar for horizontal, vertical and oblique saccades: 0.82 deg (13.07 deg) for horizontal saccades, −3.96 deg (92.48 deg) for vertical saccades, and –1.07 deg (23.34 deg) for oblique saccades. However, the distribution of the directional differences between the eyes differed significantly as a function of the direction of the saccades as shown by the Kruskal-Wallis test ($p = 0.006$). Specifically, the distribution of the directional differences between the eyes of horizontal saccades differed significantly from that of oblique saccades ($p = 0.015$). The difference between the distributions of horizontal and vertical saccades also approached significance ($p = 0.056$). No significant differences were found between vertical and oblique saccades ($p = 1.000$).

The saccade rate averaged across subjects and the three repetitions was 1.41 ± 0.69 Hz. Overall, the mean saccade rate during convergence (1.45 ± 0.66 Hz) and divergence (1.37 ± 0.74 Hz) did not differ significantly [$t(10) = 1.13 p = 0.287$]. The saccade rates of each individual participant are reported above in Table B1. The evolution of saccade rate over time was computed by using a moving time window of 1 s. As stated in the primary Results section, variations in the saccade rate as a function of the vergence demand were idiosyncratic. On average, the variation of saccade rate followed a similar behavior to the saccades detected with the clustering algorithm. Averaged across all subjects, the saccade rate decreased to around 0.5 Hz at the closest target distance (Fig. B5).

Overall, the number of saccades that corrected a horizontal vergence error (disparity) exceeded the number of error-producing saccades. This difference was close to the limit of significance [$t(10) = 2.19$, $p = 0.053$]. All subjects except three made more disparity-correcting saccades than disparity-inducing saccades (Table B2). Considering the horizontal fixation position error of each eye separately, for most subjects saccades either tended to move one eye closer to the target and the other eye either farther from the target, or produced no vergence change. The number of saccades for each subject in which the right and left eyes moved closer to the target is shown in Table B2. For all subjects except Subject 1 and the two subjects for whom eye dominance could not be established (Subjects 8 and 11), the eye with more corrective saccades corresponded to the motor-dominant eye (see the numbers in bold in Table B2).

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