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MASTER THESIS WORK

EVALUATION OF HUMAN BINOCULAR FUNCTION WITH AN EYE-TRACKER

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Evaluation of human binocular function with an eye-tracker

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Abstract. This study was designed to investigate if the velocity of the stimulus used during the near point of convergence (NPC) exam affected the performance of the vergence system. The effects of target's distance and ocular dominancy were also analyzed. 14 patients with a mean ± SD age of 26.3 ± 4.6 years participated in the study. The target used to measure the NPC was moved at three different velocities (20, 35 and 50 mm/s) along a motorized rail while the eye movements of the patient were registered with an eye-tracker. The vergence error was analyzed considering the overall range of target's distances, and the initial and final periods. The mean ± SD vergence error obtained for the total range are: 1.05º ± 0.82º (20 mm/s), 1.13º ± 0.84º (35 mm/s) and 1.24º ± 0.89º (50 mm/s). The results obtained considering the near range of distances are: 3.04º ± 1.81º (20 mm/s), 3.14º ± 1.91º (35 mm/s) and 3.36º ± 1.95º (50 mm/s). Finally, the vergence error considering the initial part of the movement are: 0.49º ± 0.15º (20 mm/s), 0.48º ± 0.13º (35 mm/s) and 0.50º ± 0.14º (50 mm/s). There are not significant differences in vergence error with the different velocities. However, the vergence error is significantly greater when more convergence is needed. Although there is no significant effect of ocular dominancy on vergence error there is a trend demonstrating that the greater the interocular difference in vergence error, the more likely the most accurate eye agreed with the dominant eye.

Keywords: Eye movements, Binocular vision, Near point of convergence, Eye-tracker, Fusional vergence.

1. Introduction

The binocular vision is the ability of both eyes to cooperate in order to produce clear bifoveal images with the information received from the two eyes separately which are then unified in the visual cortex [1]. The accommodative process consists in changing the optical power of the lens in order to allow clear vision at different distances. In normal binocular vision the vergence and accommodation systems act simultaneously.

Vergence are binocular disjunctive eye movements whose main objective is to align the fovea of both eyes with targets located at different distances [2]. Vergence can be horizontal, vertical or cyclorotary in nature, although the clinical emphasis is typically placed on its horizontal range and dynamic responsivity [3]. In convergence movements the angle between both visual axes increases in order to have a binocular single vision of a nearer object. Conversely, in divergence movements this angle decreases in order that the visual axes intersect in a further target. The vergence response can be divided into the sensory component, which senses and processes the disparity and blur inputs, and the motor component, which receives the coded disparity and blur information and generates the appropriate neuromotor command [3].

The vergence system can be divided into four components, each of them driven by a different stimulus. The disparity or fusional vergence is driven by retinal disparity. The retinal disparity is the angular positional difference at the eyes between an object in the field of view and the binocular fixation point. Then, when the disparity exceeds a threshold, i.e., Panum's fusional area, the fusional vergence generates a signal to stimulate the extraocular muscles and change the vergence angle. Accommodative vergence is the blur driven vergence. When the amount of defocus of the retinal image exceeds a threshold, i.e., the depth of focus, the accommodative system generates a signal to induce a change of the lens' power in order to obtain a focused retinal image. Concurrently, this signal is crossed over to the vergence system and produces the associated change in accommodative vergence involved in measurement of the ACA ratio [3]. The proximal vergence is driven by the perception of apparent nearness of an object. Finally, the tonic vergence is the one caused due to normal extraocular muscle tone. For this reason, the eyes of a conscious subject without any binocular or accommodative stimulus are not in the anatomical position of rest but in the physiological position of rest, which is more convergent [4]. It plays only a minor role in the overall vergence response, especially at near under standard viewing conditions [5]. These four vergence components interact nonlinearly to produce a single and clear binocular percept. In addition, the adaptive ability of these vergence components probably plays a role in the maintenance of comfortable vision during sustained near point activities [3].

Regarding vergence dynamics, the response consists of an initial fast open-loop (independent of the stimulus) component that lasts for several hundred milliseconds, followed by a slower close-loop component that reduces the residual retinal disparity [6]. The peak velocity of vergence can be related to its amplitude using a main sequence plot: vergence peak velocity increases in proportion to vergence amplitude with a ratio of 4:1 [7]. Vergence velocity is typically of the order of tens of degrees per second. The latency of vergence movements is around 200 ms when stimulus presentation is unpredictable. However, the vergence responses might precede the target jumps in response to predictable stimulus movements [6].

The vergence system is typically examined in clinical optometric practice to assess the patient's binocular function and oculomotor abilities for diagnostic, prognostic and therapeutic purposes [3]. There are many different exams to evaluate it, like the near point of convergence (NPC) or the fusional vergences. It is of relevant importance to examine it in order to diagnose possible binocular dysfunctions, which are sometimes associated with symptoms such as headache, blurred vision or double vision. The most common binocular dysfunction is convergence insufficiency, with a prevalence ranging from 2.25% to 33% depending on the studied population [8].

The NPC is the nearest point in the space where an individual can maintain binocular fusion [9]. The purpose of NPC is to assess the convergence amplitude. It is performed by slowly moving a target along the midline towards the eyes until the patient reports diplopia or the examiner notices a break in fusion by observing the patient's eyes [10]. This is recorded as the break point. The target is then slowly moved away from the patient until single vision is recovered or the examiner notices realignment of the eyes. This is recorded as the recovery point. The point at which the patient reports that the target appears double (subjective) or the examiner observes that one eye loses fixation and turns outward (objective) is taken as the NPC. The numerical value attributed to the NPC is obtained by measuring the distance from these points to the corneal plane using a ruler [11]. The patients are asked to maintain single vision during all the test. To accomplish this, they use a combination of various components of convergence including accommodative convergence, positive fusional convergence and proximal convergence. If any of this components are deficient, it may affect the patient's ability to achieve the expected finding on the NPC test.

Different targets can be used to perform the NPC, like the RAF rule, a pencil tip, a fingertip, or a penlight placing a red filter before one eye [12]. There is controversy regarding the effect of the target on the results of the test. Several studies reported that the results obtained measuring the NPC depends on the target that is used. Paul M. Adler et al. (2007) exposed that the use of an accommodative target gives a more accurate assessment of convergence ability than a non accommodative target such as a penlight [12]. In contrast, according to the results, the detail of the accommodative target is irrelevant [12]. However, John Siderov et al. (2001) concluded that NPC does not depend on the target used since they found similar results when the NPC was measured with the RAF rule, a pencil tip or a finger tip [11]. Other studies recommended to repeat the NPC twice; first using an accommodative target and then using a transillumination or penlight with red-green glasses [10].

The normal values of the NPC are considered to be less than 10 cm for the break point and less than 15 cm for the recovery point. Poor results in some binocular exams leads to the diagnostic of binocular disorders such as convergence insufficiency. A remote NPC with a break greater than 10 cm is considered the most consistent finding of this binocular dysfunction [10].
Some studies found that 93% of optometrists' respondents to a survey indicated that they consider NPC as a factor in making a diagnosis of convergence insufficiency [13]. Other studies concluded that the evaluation of NPC is more important in people with high near task demands [14]. Moreover, in a different study about the measurement of the NPC in elementary school, the break and recovery values were analyzed as a function of the symptoms of the patients. It was found that the break value can be statistically predicted in the symptomatic cases [15].
The NPC, as well as the other tests to assess the binocular function are subjective since they depend on the answers of the patients and the ability of the examiner. In most of the cases, the patients need to report when they perceive double vision and/or when they recover single vision. Nevertheless, these tests are closely related with the assessment of the oculomotor function, especially the vergence system. The eye movements can be evaluated objectively using eye-trackers. Although its use is relatively rare in current clinical practice, registering eye movements with these devices offers significant advantages such as the possibility to assess quantitatively eye movements' characteristics or achieve higher spatial and temporal resolution than with naked eye observations. Moreover, they are widely used in vision research.
In this sense, the main objective of this study is to analyze the vergence movements registered with an eye-tracker during the performance of the NPC. The vergence error, i.e., the difference between the stimulus vergence and the vergence response, will be analyzed as a function of the distance and the velocity of the stimulus.

2. Methodology

2.1. Experimental setup

The experimental setup used in this study can be seen in Figure 1. A motorized rail was assembled on a metallic mount. The visual stimulus consisted in a black line with a height of 6º and width of 0.1º at 40 cm with a crosshair at the middle. It was hung from a light metallic structure fixed on the motorized rail. The range of possible positions of the stimuli spanned from 57 cm to 5.7 cm away from the eyes of the patient.

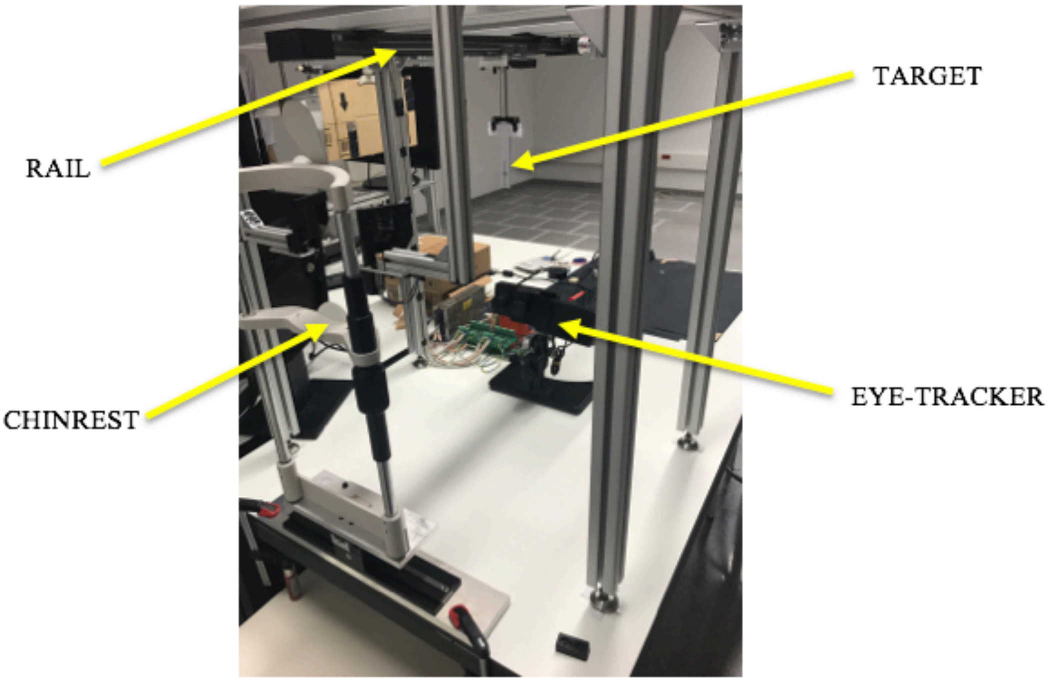

Figure 1. Experimental setup configuration.

The eye-tracker Eyelink 1000 Plus (SR-Research Ltd., Ontario, Canada) was used to record the eye movements while the patients watched the moving stimulus. This device used an infrared emitter (940 nm) and a camera to track the eyes either monocularly or binocularly. In this study, the eye movements were registered binocularly at a frame rate of 500 Hz. This sampling rate largely exceeds the Nyquist sampling criterion for the measurement of vergence movements. The average accuracy of the system is typically lower than 0.5º according to manufacturer's reports. The patients' movements were limited by a chinrest centered on the experimental setup.

2.2 Subjects

18 patients (mean ± standard deviation (SD) age 27.4 ± 6.7 years) participated in the study. They had normal or corrected to normal visual acuity and wore their habitual refractive correction (either glasses or soft contact lenses) during the experimental procedure. All had a NPC lower than 5 cm measured with a pen tip. Results were only analyzed from subjects who did not experience diplopia during any of the measurements of the NPC. Moreover, recordings had been visually inspected to detect the measurements in which the patient did not report double vision although one eye clearly lost fixation. After rejecting these cases, the recordings of 14 patients (mean ± SD age 26.3 ± 4.6 years) were selected for further analysis.

2.3. Experimental procedure

Before starting the measurements with the eye-tracker, the motor ocular dominance was assessed using the Hole-in-the-Card test [16], and the interpupillary distance and the NPC were measured by an optometrist. The stimulus used was a pen tip. The NPC was measured three times and the average of all measures was computed. After that, the patient was positioned on the chinrest and properly aligned so as that the movement of the target induced symmetrical convergence.

During the eye-tracker calibration, the patients were asked to fixate binocularly each of the 9 stimulus located in a 3x3 grid. Each stimulus consisted of a combination of a black circle with a white cross and subtended an angle of 0.9º at 40 cm (the distance at which the calibration was performed). Once the calibration was finished successfully, the measurements of the NPC started. The motor that moved the stimulus was controlled using Matlab R2015b (MathWorks, Natick, MA). The NPC measurement was performed with three different stimulus' velocities: 20 mm/s, 35 mm/s and 50 mm/s. The order of the velocities in each session was randomized. First, the stimulus remained at 40 cm for 2 seconds. Then, it started moving forwards and the patients were asked to look at the center of the crosshair and press a key of the keyboard when they perceived the stimulus double. The stimulus remained 2 seconds in the closest evaluated position (7.5 cm to the eyes). Finally, it moved backwards and the patients were asked to press a key when they recovered single vision. This procedure was repeated five times for each velocity. Then, all the measures were repeated in a second session separated by a rest of at least 30 minutes.

2.4. Eye movements analysis

Eye movements recordings were analyzed with a custom Matlab program. The interpupillary distance of each subject was measured to calculate the correct vergence angles of both eyes, and the overall vergence response was calculated by subtracting the right eye data from the left eye data (Figure 2). Blinks were detected by the eye-tracker's software and samples 100 ms before and after these periods of data loss were linearly interpolated. Only the periods of convergence, i.e., the periods when the stimulus moved towards the patient, were analyzed. The five convergence responses were averaged for a more robust analysis.

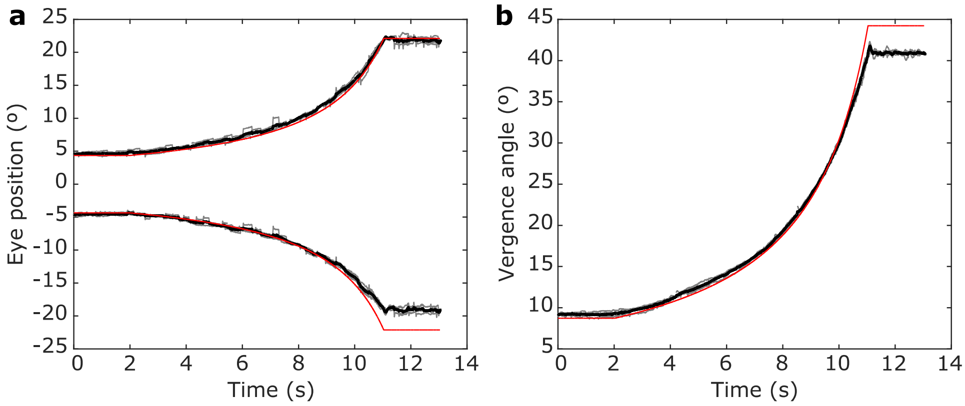

Figure 2. Plots of right and left eyes position (a) and vergence angle (b) as a function of time. Gray traces are individual responses, black lines are the average of the five individual responses, and the red line shows the position of the stimulus.

The vergence error was quantified as a single figure index that characterizes the stimulus-response curve. This index was initially proposed by Chauhan and Charman (1995) to evaluate the accuracy of the accommodative response [17]. However, we think that it can be also applied to assess the error of the vergence system. The vergence response is compared to the stimulus curve using linear regression analysis (Figure 3). Then, the vergence error index is a combination of the slope of the linear regression, its intercept on the y-axis and the correlation coefficient. Specifically, it is computed as

$$I = \frac{\int_{x_1}^{x_2} [y - y\prime]\, dx}{\int_{x_1}^{x_2} dx} \cdot r^{-2} \qquad (1)$$

where I is the vergence error index, x_1 and x_2 are the limits of the stimulus interval, y is the unit response $y=x$, y' is the best fit line, and r^2 is the Pearson correlation coefficient.
The vergence error index was computed for each measurement for the overall movement of the stimuli (I), considering only the initial 10% of the movement (I_{far}) and considering the final 10% (I_{near}).

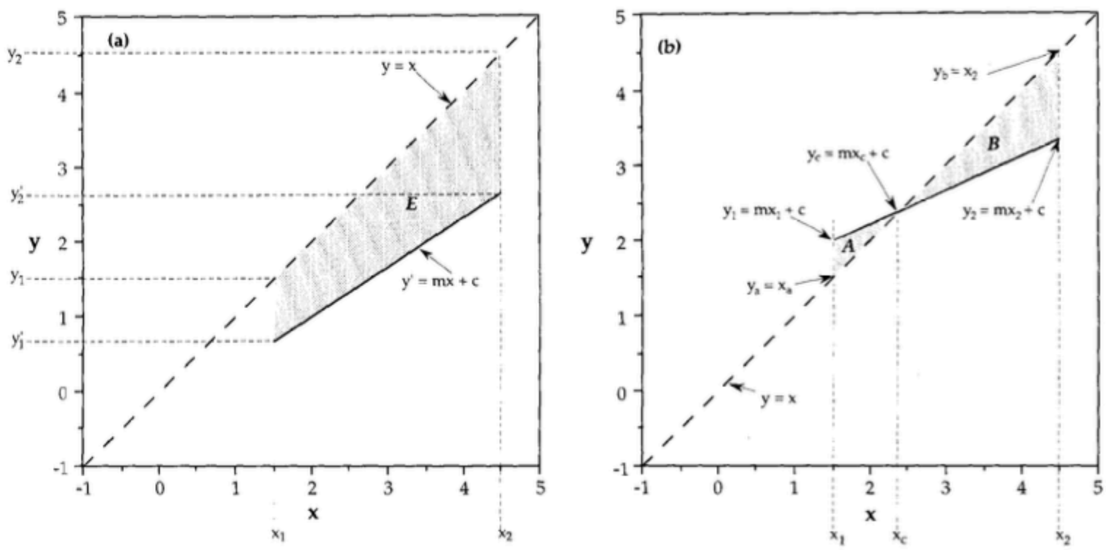

Figure 3. An illustration depicting the method of calculating the area between the actual and the perfect response lines over a chosen stimulus interval. The x axis represents the stimulus and the y axis represents the response. The solid line in both figures is the best fit regression line through a set of data points. The dashed line is the perfect or unit response. (a) depicts a situation where the regression line (y'= mx + c) does not intersect the unit response (y = x). The area, E, between the curves is shaded (b) despicts a situation where the regression line does intersect the unit response. The shaded area between the two curves is divided into two parts, A and B [17].

2.5. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 23 (IBM; Armonk, NY). Significance was set at p<0.05. Normality of each variable was checked by applying the Shapiro–Wilk test. A repeated measures ANOVA was performed to analyze the effect of velocity on the vergence error considering the complete range of stimulus' distance (I). A two-way repeated measures ANOVA with the factors stimulus' distance and velocity was used to analyze the interaction effects between these variables. If significance was obtained, the Bonferroni *post-hoc* was applied for pairwise comparisons. Finally, a paired t test was performed to determine intereye differences in vergence error due to ocular dominance.

3. Results

First, the results of both sessions were averaged in order to obtain more robust results and a higher statistical power. In a preliminary analysis, no significant differences were found between the first and second sessions for neither velocity.

Table 1 give descriptive statistics (mean ± SD) of the vergence error considering the overall range of distances (I), the initial 10% of the movement (I_{far}) and the final 10% of the movement (I_{near}) for the three tested velocities. It can also be seen in Figure 4.

Table 1. Mean ± SD of vergence error in degrees considering the different ranges of distances for the three tested velocities.

Velocity	I (º)	I_{near} (º)	I_{far} (º)
20 mm/s	1.05 ± 0.82	3.04 ± 1.81	0.49 ± 0.15
35 mm/s	1.13 ± 0.84	3.14 ± 1.91	0.48 ± 0.13
50 mm/s	1.24 ± 0.89	3.36 ± 1.95	0.50 ± 0.14

Three different effects on vergence error have been studied: the effect of target's velocity, the effect of target's velocity and distance and the effect of ocular dominancy.

Regarding the effect of target's velocity on vergence error considering the overall range of distances, on average there is a slight trend of increasing error with the velocity. The repeated measures ANOVA showed a significant effect of velocity on vergence error ($F(2,26)=4.17$, $p=0.027$). However, the Bonferroni post-hoc test showed no significant differences between any pairwise comparisons ($p>0.05$).

To analyze the effect of target's velocity and distance on vergence error, a two-way repeated measures ANOVA was performed. There was not a significant interaction between the effects of velocity and distance ($F(2,20)=1.96$, $p=0.167$). The main effect of velocity on vergence error considering the initial 10% and the final 10% of the movement was at the limit of significance ($F(2,20)=4.13$, $p=0.031$) and the Bonferroni post-hoc test showed no significant differences between any pairwise comparisons. The main effect of target's distance on vergence error was statistically significant ($F(1,10)=23.26$, $p=0.001$). The vergence error at the final 10% of the movement was significantly greater than the error at the initial 10% with a mean difference ± SD of 2.7º ± 1.85º.

In 8 subjects (57.1%) the dominant eye was the right eye and in 6 (42.9%) it was the left eye. On average, the error was lower in the dominant eye and the differences were higher when the final 10% of the movement was considered. However, the paired t test showed no significant effect of ocular dominancy on vergence error: mean difference ± SD of 0.19º ± 1.62º ($p=0.663$) for 20 mm/s, 0.29º ± 1.80º ($p=0.553$) for 35 mm/s and 0.47º ± 1.51º ($p=0.304$) for 50 mm/s.

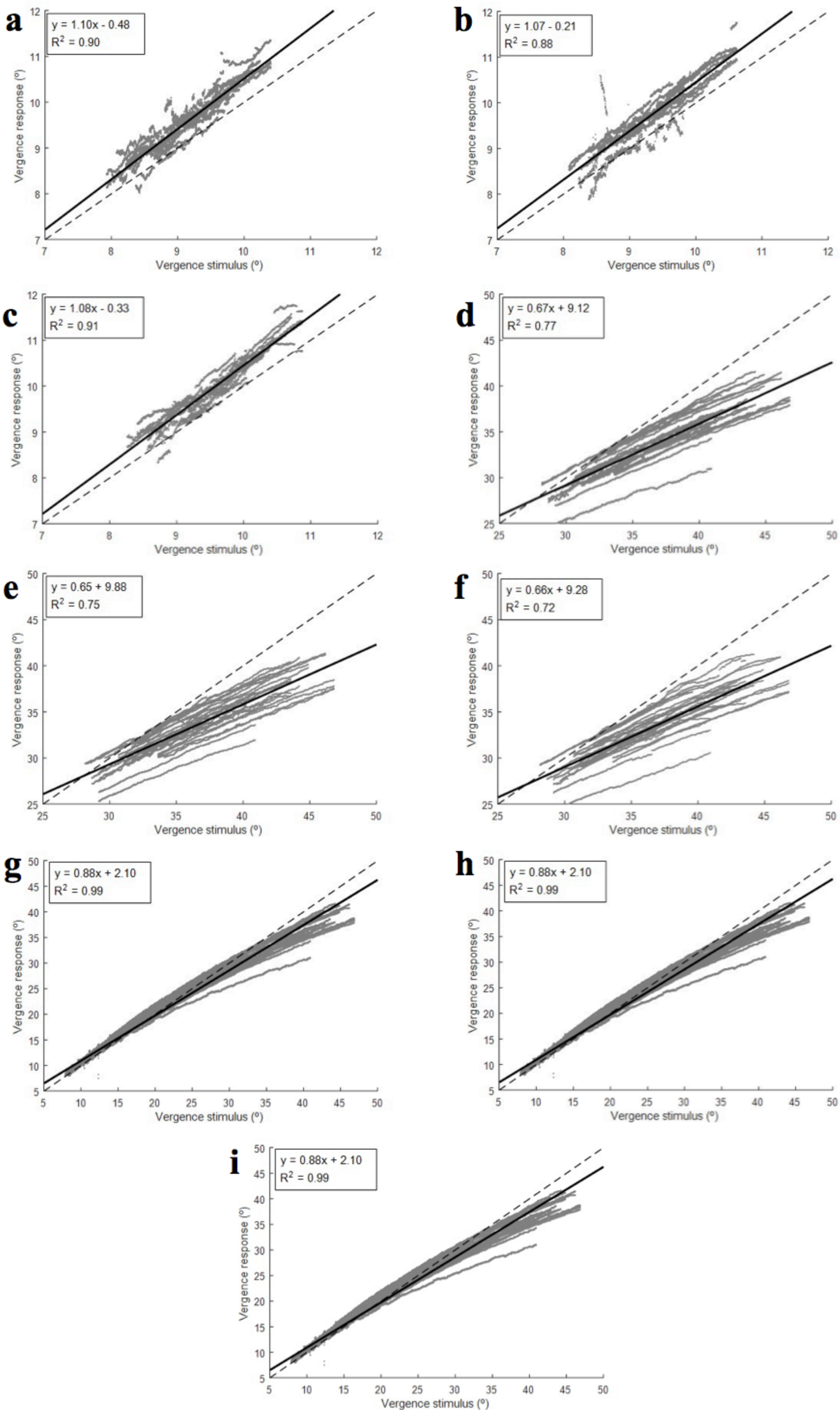

Figure 4. Plots of vergence error considering the initial 10% of the movement (I_{far}) (a, b, c), the final 10% of the movement (I_{near}) (d, e, f) and the overall range of distance (I) (g, h, i) for the three tested velocities (20, 35 and 50 mm/s, respectively). The dashed line is the perfect or unit response. The gray lines are the average response of the 14 patients. And the black solid line in all plots is the best fit regression line through the set of data points. The fitted line's equations and the coefficient of determination are represented in each plot.

Regarding individual cases, in approximately 50% of the subjects the greatest error was seen in the non dominant eye. However, there was a trend demonstrating that the greater the interocular difference in vergence error, the more likely the most accurate eye agreed with the dominant eye (Figure 5).

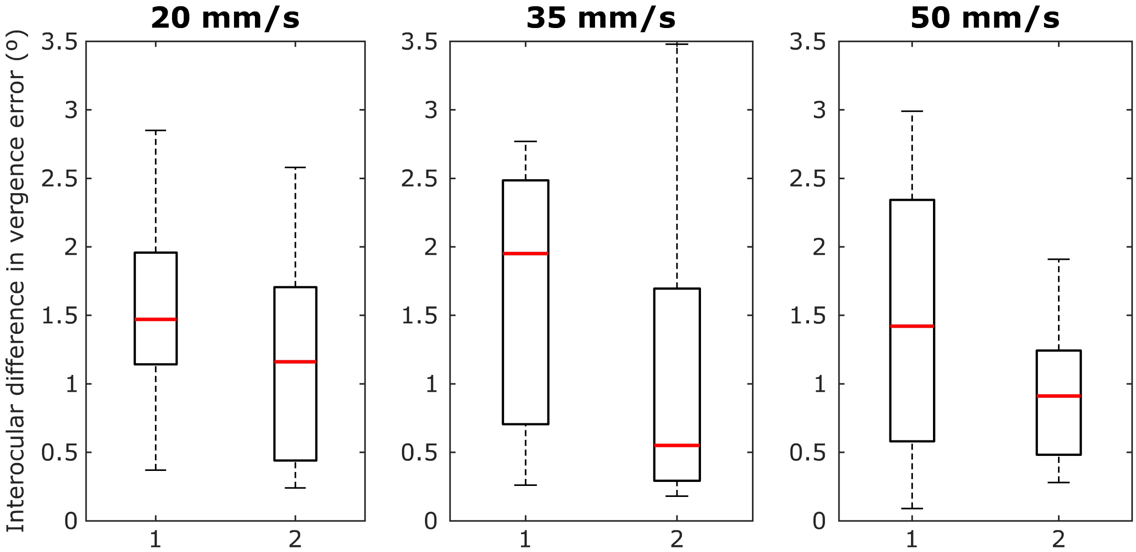

Figure 5. Boxplots showing the difference in vergence error between eyes when the dominant eye coincided with the one with lower vergence error (1 in x-axis) and when they did not agree (2 in x-axis). There is one boxplot for each target's velocity used in the experiment: 20 mm/s, 35 mm/s and 50 mm/s.

4. Discussion

In the present study, the effect of changing the velocity at which the target is moved during the NPC test has been analyzed. The results showed a slight trend of increasing the vergence error with higher velocities, although the differences were not statistically significant. This agreed with a previous study by Erkelens et al. (1989), who concluded that the vergence error remained rather constant around 1° for vergence speeds up to 20 °/s and rose sharply for faster velocities [18]. Although the vergence velocities tested in our study were not constant (they were constant in terms of linear stimulus' displacement), they never exceeded 20 °/s. Thus, our finding of no significant effect of velocity on vergence error might be due to the chosen velocities. The aim of this study was not to find the highest human vergence velocity but to analyze the accuracy of vergence movements as a function of feasible target velocities during the performance of the NPC.
Regarding the effect of target's distance on vergence error, there is a tendency towards overconvergence at far (40 cm) and underconvergence at near as can be seen in Figure 4. This trend was also observed in [19] with vergence step stimuli instead of smoothly increasing vergence angle. The significantly larger vergence lag found at near together with a considerable variation on the results between subjects was consistent with previous studies that analyzed vergence movements in natural conditions [19]. Nevertheless, Sweeney et al. (2014) analyzed the stimulus response curve for the vergence movements when the accommodative system was open loop (no blur stimuli) and obtained a vergence lag similar across all tested stimulus levels (stimulus distances from 100 cm to 14,3 cm) [20]. Thus, it is hypothesized that the increased vergence error at near might be explained by the accommodative vergence component and the interactions between the vergence and accommodation systems.
The effect of ocular dominancy on vergence error was also studied. The subjects showed a rather typical distribution between right eye and left eye dominance [21], [16]. The vergence error was computed separately for right and left eyes. The highest interocular differences were found when the final 10% of the movement was considered, so when the target was at the closest distance to the patient. According to the results, the vergence performance of the dominant and non dominant eye was not significantly different. However, there was a trend showing that the greater the interocular difference in vergence error, the more likely the most accurate eye agreed with the dominant eye. Similar results were obtained by Johansson et al. (2014) when they compared the

monocular and binocular reading performance in subjects with normal binocular vision [22]. This might indicate that the dominance tests may predict performance superiority when there is a pronounced performance difference, as previously stated by Johansson et al. (2015) [16]. From the results of this study and the previous research described, it appears that the strength of eye dominance, which cannot be assessed with the Hole-in-the-Card test, might play a role in defining the performance superiority of the dominant eye on any oculomotor task [16].

5. Conclusion

NPC is the most important diagnostic parameter in convergence insufficiency and it helps to monitor the improvements achieved after treatment. For this reason, it is important to perform this test in a more standardized way than in conventional clinics and analyze objectively its results. In this work, the movement of the stimulus has been controlled mechanically and the eye movements elicited have been studied objectively. The differences in vergence error due to changes in the target's velocity and distance during this exam have been analyzed.

The results suggest that the vergence error does not vary with the target's velocity, at least at the feasible range of speeds typically used in the clinical test. However, it increases significantly when the stimulus is placed at nearer distances. In this situation, when the patients achieve the maximum convergence and the visual system is at a more stressful situation, the vergence error rises considerably.

Although a clearly superior vergence performance of the dominant eye is not demonstrated, the degree of eye dominance might explain to some extend the intereye differences found in this study. Further research is needed to study this effect and its clinical implications.

6. References

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