UNIVERSITY OF LATVIA
FACULTY OF PHYSICS AND MATHEMATICS

EXPERIMENTAL STUDY OF VERGENCE RESPONSE AND FIXATION DISPARITY

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Abstract

From clinical perspectives, it is not always sufficient to know whether a person has a large or small fixation disparity, rather it might be important to understand, which underlying physiological mechanism is involved in the origin of this fixation disparity. Therefore, the aim of the present study is to investigate dynamic properties of vergence response in both convergent and divergent direction and to test to what extent they can be used to determine the origin of fixation disparity together with other underlying physiological mechanisms in a group of randomly chosen participants. Additionally, we explored – on the bases of previous studies – the subjective method with dichoptic nonius lines to provide physiologically plausible estimation of individual differences in dynamic asymmetry of vergence.

The study was organized in three experiments, each focusing on some important parts of the study. Fixation disparity and vergence response were measured subjectively using nonius technique and objectively using the video-based eye tracker (EyeLink II, 500 Hz binocular monitoring) during the time period from 2006 to 2009. To present dichoptic separation, we used two techniques – liquid crystal shutter glasses (Elsa Revelator, 60 Hz refresh rate) and a mirror stereoscope.

Our results demonstrate that the individual differences in the asymmetry of vergence dynamics in convergent and divergent direction were able to explain at most 50% (r^2) of the inter-individual variance in fixation disparity in the present group of participants. If dark vergence and nonius bias are added to dynamic asymmetry, this combination of factors explains 62% (r^2). Combination of heterophoria (where accommodative factor is involved) and nonius bias explains 74% (r2). Accordingly to these observations, we can conclude that the clinically relevant subjective fixation disparity originates from distinct physiological sources and from the nonius bias as an artifact of the nonius method.

Keywords: Fixation disparity, vergence, dark vergence, heterophoria.

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1. Introduction – the history of fixation disparity studies

About 80% of information is obtained with visual system. As we have two eyes, one of the functions of visual system is to fuse the images of both eyes. For stable single vision, the fusion system keeps the images of the two eyes on corresponding points as close as possible. However, fusion is not always exact: a difference may occur between the physical position of the target and the point actually fixated by the eyes, i.e., the intersection point of the two visual axes during binocular fusion; this difference is called fixation disparity. The two visual axes may intersect in the plane of the fixation target, in front of or behind it; these conditions are known as zero, eso or exo fixation disparity, respectively (see Figure 1.1). Even if there is eso or exo fixation disparity, the images of both eyes still lie within Panum's area and, therefore, observers do not experience diplopia or changes in the quality of the image[1-2].

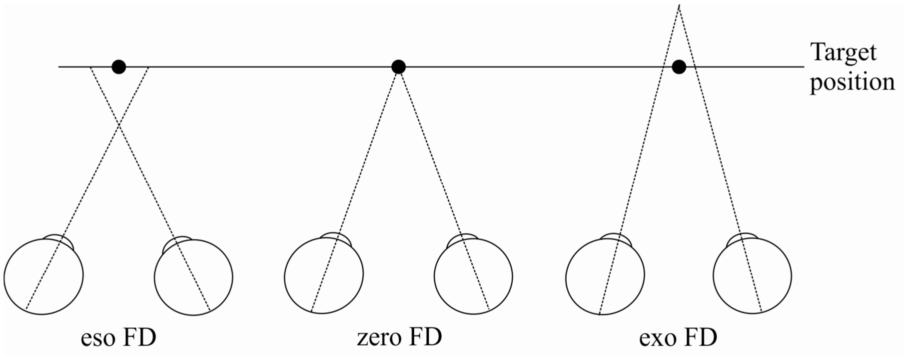

Figure 1.1. Illustration of fixation disparity (FD), where two visual axes intersect in the plane of the fixation target, in front of or behind it.

The first mention of the phenomenon known as fixation disparity can be found in 1900 in works of Hofmann and Bielschowsky described by Ogle in his book[2]. Ogle[2-3] described fixation disparity wider, especially concentrating on the changes of fixation disparity under prism load and relating his findings to asthenopia. Prisms change stress on the binocular alignment system and, thus, change the amount of fixation disparity. Prism base-in (base-out) is forcing eyes to diverge (converge) to maintain fusion. If the convergence-accommodation reflex is active, the visual system is resisting to any changes of vergence because it would change accommodation causing blurring. Unlike diverging (converging), the eyes can use Panum's area to fuse images even remaining very slightly convergent (divergent) relative to divergent (convergent) demand. Thus, visual axes are creating eso (exo) fixation disparity. With increasing prism load, fusion is kept till the limit of fusion reserves where fusion becomes too unsteady for a reliable judgment or diplopia occurs[3]. Some observers cannot achieve the endpoint of measurement because of blurring or ocular discomfort. Similar effect on fixation disparity was produced by spherical ophthalmic lenses[3].

Ogle[3] observed that fixation disparity changes produced by prisms or ophthalmic lenses differ greatly with individuals and it is a result of disturbance in the convergence-accommodation reflex mechanism. He described four major types of prism induced fixation disparity curves (see Figure 1.2).

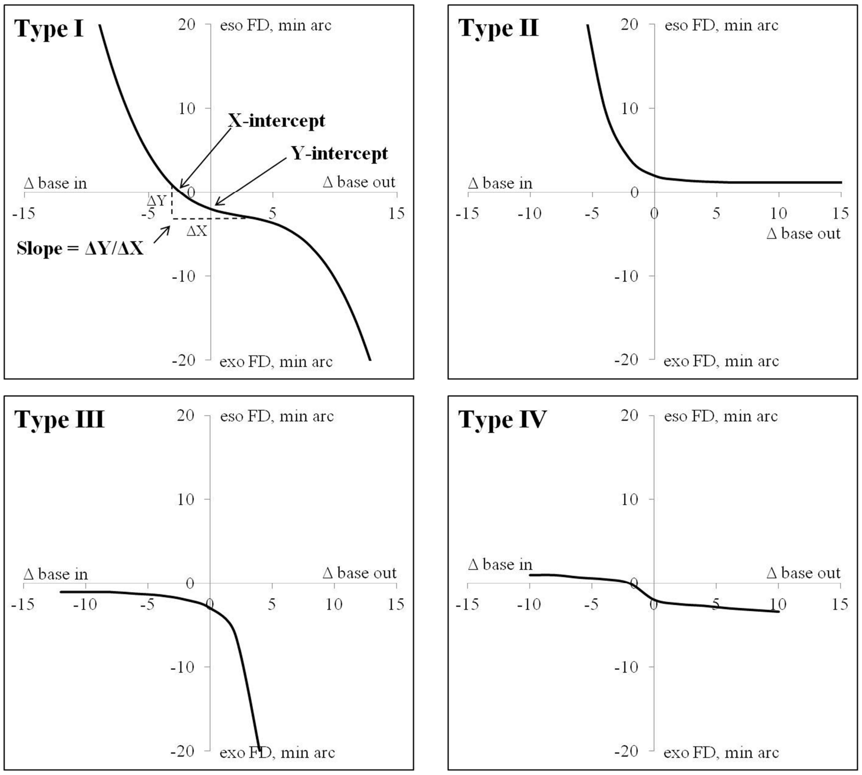

Figure 1.2. Types of prism induced fixation disparity (FD) curves and their parameters (shown for type I).

In type I (observed more often, 60%)[1], fixation disparity is increasing more rapidly and fairly equally both for prisms base-in and base-out. Thus, it probably represents normal functioning of vergence system. Type II is mostly associated with esophoria and show good adaptation to prisms base-out keeping fixation disparity constant till diplopia appears. In opposite direction (with prisms base-in) vergence is functioning fairly weak. Type III is associated mostly with exophoria and show good adaptation to prisms base-in and weak to base-out. Type IV usually is observed in persons with poorly developed binocular coordination, especially for near vision. Fixation disparity is changing only in a very narrow interval and outside that interval it is braking off at nearly constant values. Usually accommodation is changing in response to prism load and associated vergence changes. Thus, blurring, uncertainly, and even suppression occur at very low prism values[3].

Following the studies of Ogle, Sheedy[1] suggested some indications prescribing therapy based on the results measuring prism induced fixation disparity curves. Prism induced fixation disparity curves were analyzed in clinical cases describing type (from I to IV), the slope (steep or flat), X-intercept (named also associated phoria), and Y-intercept (fixation disparity in natural condition without added prism) of the curve (see Figure 1.2). It is believed that the slope greater than 1.0 is mostly associated with asthenopia. Whereas, the type of the curve can show whether it will be enough just to train or also prisms should be prescribed to eliminate asthenopia.

Ngan et al.[4], Ogle[2], Frantz[5-6] studied the effect of subjective methods used for measuring fixation disparity: Wesson fixation disparity Card, Saladin fixation disparity, Disparometer. The main explanation of different fixation disparity results with different measurement methods was due to the method itself – mostly due to the size and position of fusion stimulus. For example, Ogle[2] observed that the steepness of the curve and Y-intercept is changed by increasing fusional stimulus and shifting it to the periphery. This influence is variable among different types of prism induced fixation disparity curves. If only peripheral fusional stimulus is presented, eyes tend to deviate more from ortho position. That could be explained by Panum's area, which is larger in the periphery than in the centre. Panum's area is smaller in centre, if small details of fixation objects should be analyzed. If there is no common central fixation object, Panum's area can increase allowing larger misalignment of two eyes. But sometimes, including central fixation stimulus also is not so successful while monocular nonius lines can compete with binocular background, causing suppression in their surroundings[7].

Based on the principles of position of fusion stimulus, Goersch[8-10] summarized the works of H.-J.Haase and described some other method of measuring fixation disparity. He described three stages of measurements (first form of fixation disparity, young and old second form of fixation disparity). He suggested to correct heterophoria (mainly prism correction) based on the measurements of all three forms of fixation disparity. However, this method is quite complicated and time-consuming, therefore not widely used to evaluate fixation disparity.

Subjectively measured (like with dichoptic nonius lines) fixation disparity varies among subjects with normal binocular vision and typically amounts to a few minutes of arc – most often less than 10 min arc and nearly always less than 25 min arc[1-2]. Ogle[3] observed that the fixation disparity can get larger with lowered visual acuity and under different conditions like forced vergence produced by prisms as the fusion of the images becomes more unstable. Ogle[3] supposed that "the magnitude of the disparity depends upon the strength of the innervations to the extrinsic muscles of the eyes during fusion, the degree of heterophoria, the strength of the fusion processes themselves and the amount and complexity of the detail in the binocular field of view." The visual system is trying to keep both images as close as possible to the corresponding points on the retina, but because of existing muscular imbalance the fusion is not exact. He argued that "the FD is a measure of muscular imbalance between two eyes while fusion is maintained. This imbalance must be the resultant stress not only of mechanical and of tonic neuromuscular factors, but also of functional innervations of a different order arising from fusional stimuli."[3] Kommerell[7] suggests that both dissociated phoria (the vergence angle obtained in prisms to correct heterophoria) and associated phoria (the vergence angle obtained in prisms to correct fixation disparity) are "reactions to an artificial interference with binocular vision". He observed that fixation disparity gradually developed under the artificial conditions during subjective fixation disparity measurement with Haase's clock hand test for fixation disparity, but was not observed during natural viewing conditions (as registered with eye tracking method). He concluded that these subjective methods used to measure fixation disparity "do not correctly indicate the vergence position of the eyes under natural viewing conditions".

Therefore, there are attempts to measure fixation disparity objectively in the later studies[11-14]. These studies show discrepancy between results. Objectively measured fixation disparity is considerably larger (ranging even up to 60 min arc[14]) than subjectively measured fixation disparity. There are a lot of disputes about the reason of this difference.

Despite the difference between subjective and objective measurements of fixation disparity, there are also numerous disputes regarding the origin of fixation disparity. One classical concept maintains that fixation disparity may be a condition of stress on the vergence system[2], where larger amounts of fixation disparity or steeper forced fixation disparity curves indicate a less adaptive vergence system[15]. In computational models, fixation disparity is explained by the gain of the dynamic vergence properties. The gain represents the velocity of changes in the vergence angle. Dynamic changes in vergence occur changing fixation between near and far objects or presenting a disparity stimulus on monitors in the laboratory. In feedback control theory-based models[2,16-19] fixation disparity is a necessary error to stimulate the fusional vergence system. Control theory-based models incorporate a gain factor for just one direction of disparity vergence step stimuli, i.e., either convergent or divergent (relative to baseline). In order to provide predictions for each direction, the model must be applied separately with vergence gain factors that may be different for the two directions.[20-21]

Patel et al.[22-23] described a neural network model that directly incorporates two vergence directions – two opponent pathways for convergence and divergence. Accordingly, fixation disparity is predicted to be proportional to the asymmetry in convergent and divergent dynamic responsiveness[22-23]. Thus, an eso (exo) fixation disparity results if the convergent velocity is larger (smaller) than the divergent velocity[23]. In cases with zero fixation disparity, the gain of dynamic vergence responses in both directions should be equal. Patel et al.[23] provided evidence for this prediction from an intra-individual approach: a linear relation between fixation disparity and dynamic asymmetry was found in each of five observers when the load on the vergence system was increased by crossed disparity.

An intra-individual approach (made for a few subjects) does not answer the question whether the large inter-individual variability in fixation disparity could be explained by individual differences in the asymmetry in vergence dynamics. Evidence for this inter-individual relation was indirectly provided by Fredenburg and Harwerth[24]. Among their six subjects, two subjects with a large convergent, but missing divergent dynamic response had an eso fixation disparity, while two other subjects with a large divergent, but missing convergent dynamic response had an exo fixation disparity. One subject with symmetric dynamic response had no fixation disparity. Thus, most subjects of Fredenburg and Harwerth[24] support a relation between fixation disparity and the asymmetry in vergence dynamic. But they did not use a measure of vergence velocity for a given disparity step amplitude as suggested by the neural network model of Patel et. al.[22-23], rather their measure of asymmetry was based on the extent to which the response increased with the disparity stimulus (0-30 min arc).

Regarding the theoretical framework used to explain fixation disparity, Patel et al.[23] have also mentioned the possible influences of vergence adaptation, proximal cues, viewing distance, heterophoria and dark vergence on fixation disparity. The authors supposed that when observing fixation disparity "under conditions that eliminate (or keep fixed) the aforementioned parameters (i.e., in the absence of adaptation, for stimuli without proximal cues, when accommodation input and viewing distance are kept constant), that these are modulatory effects, rather than being the basic neural origin of fixation disparity. These factors may affect fixation disparity indirectly via changes in vergence dynamics".[23] Like in a clinical practice, it is not possible to eliminate all of previously mentioned factors, fixation disparity can be directly influenced not only by vergence dynamics, but also by different other factors changing the state of vergence system. Nevertheless, the relative contributions of these modulating factors in determining vergence dynamics and fixation disparity should be investigated in more detail.

Therefore, **the aim** of the present study is to investigate dynamic properties of vergence response in both convergent and divergent direction and to test to what extent they can be used to determine the origin of fixation disparity together with other underlying physiological mechanisms in a group of randomly chosen participants. Additionally, we explored – on the bases of previous studies – the subjective method with dichoptic nonius lines to provide physiologically plausible estimation of individual differences in dynamic asymmetry of vergence.

The work was organized in three parts, each having its own **purposes**.

1. Relation between fixation disparity and the asymmetry of convergent and divergent disparity step responses (Experiment I):
    1.1. To evaluate the reliability of the nonius method used to subjectively measure fixation disparity and vergence response at 60 cm viewing distance.
    1.2. To determine the amount of inter-individual variance in fixation disparity that can be explained by individual differences in the asymmetry of vergence dynamics evaluated at 60 cm viewing distance for a disparity step stimulus of 60 min arc (1°).
2. Dynamic and static parameters of vergence response with changing viewing distance and disparity vergence step stimulus size (Experiment II):
    2.1. To evaluate the reliability of the nonius method for subjectively measuring vergence responses in two conditions of vergence load: (1) changing viewing distance (30 cm, 40 cm, 60 cm, and 100 cm) and with constant step stimulus size (60 min arc), and (2) changing vergence step stimulus size (15 min arc, 30 min arc, 60 min arc, 120 min arc) at constant viewing distance (60 cm).
    2.2. To explore the subjective method with dichoptic nonius lines to provide physiologically plausible estimation of individual differences in dynamic asymmetry of vergence.
    2.3. To investigated the effect of distance and disparity step stimulus size on the correlation between fixation disparity and individual differences in the asymmetry of vergence dynamics.
3. A multiple regression model to explain inter-individual differences in subjective

fixation disparity (Experiment III):

- 3.1. To compare fixation disparity and vergence step response obtained both with nonius technique and with eye tracker.
- 3.2. To what extent the inter-individual variability of subjectively measured fixation disparity can be explained by combination of underlying physiological mechanisms as vergence step response asymmetry, dark vergence, heterophoria, and nonius bias.

The whole study is relevant since from clinical perspectives it is not always sufficient to know whether a person has a large or small fixation disparity, rather it might be important to understand, which underlying physiological mechanism is involved in the origin of this fixation disparity. The dynamic asymmetry of vergence response is in the focus of this study since the relation between fixation disparity and dynamic asymmetry of vergence response had not yet been investigated with an inter-individual approach or in a larger group of randomly chosen participants. Eye trackers are mostly used in research to measure vergence responses objectively but are not always applicable in routine clinical test procedures. Therefore, this study evaluates the advantages and disadvantages of a technically more simple nonius technique referred as subjective method.

2. Method

Three types of fixation disparity and vergence response evaluation experiments (Experiment I, Experiment II, and Experiment III) were performed during the time period from 2006 to 2009 partly in Department of Optometry and Vision Science of University of Latvia, Riga, Latvia and in the Leibniz Research Centre for Working Environment and Human Factors (Leibniz-Institut für Arbeitsforschung an der TU Dortmund (IfADo)), Dortmund, Germany. The procedure used in all experiments was based on nonius technique and was developed in the Leibniz Research Centre for Working Environment and Human Factors (Leibniz-Institut für Arbeitsforschung an der TU Dortmund (IfADo)), Dortmund, Germany. The procedure is previously tested and described in many publications[25-31] and in the homepage of the Institute as an eye-test-PC (www.ifado.de).

2.1. Apparatus

The procedure requires one (or two in a mirror stereoscope) computer for stimulus presentation and one computer for controlling procedure. To present dichoptic separation, we used two techniques – liquid crystal (LC) shutter glasses (Elsa Revelator, 60 Hz refresh rate) (in Experiment I and Experiment II) and a mirror stereoscope (in Experiment III). Thus, the test computer and a monitor or monitors to present stimulus depended on the technique used.

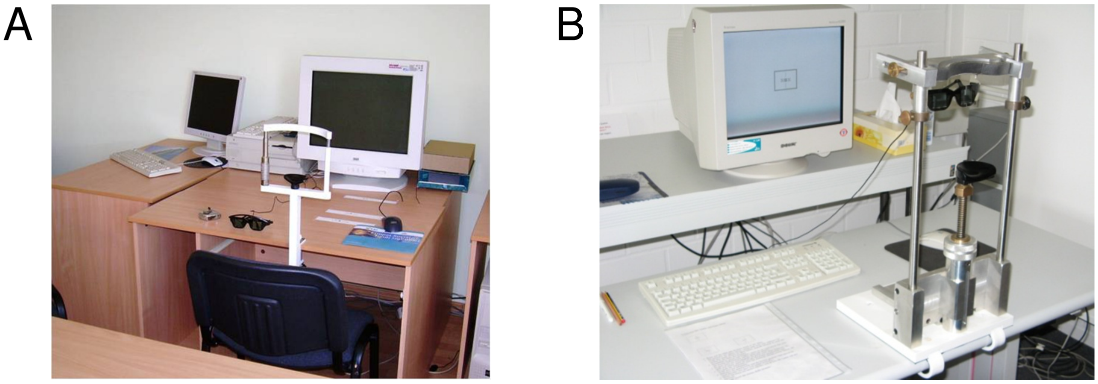

Figure 2.1. Schematic position of the test computer using LC shutter glasses in Department of Optometry and Vision science (University of Latvia, Riga, Latvia; A) and in the Leibniz Research Centre for Working Environment and Human Factors (Leibniz-Institut für Arbeitsforschung an der TU Dortmund (IfADo)), Dortmund, Germany; B). The photos reprinted with courtesy of Ifado.

The technique using LC shutter glasses requires one CRT monitor for stimulus presentation. The series of consecutive frames are presented alternatively to the left and right eye by switching the optical transmission of the shutter glasses between closed and transparent synchronously with the refresh rate of the CRT monitor (see Figure 2.1). Using this technique, we subjectively measured fixation disparity and vergence step response.

At a mirror stereoscope, the images for both eyes could be presented on two displays or on smaller areas on one display. For our experiment, we used two thin film transistor liquid crystal display (TFT-LCD) monitors (one for each eye). The separate images are combined with mirrors at right angle (see Figure 2.2). Due to the mirrors placed close to the eyes, the edges of the monitors were not visible for the participant. Thus, there were no direct fusion targets helping the participant to fuse targets other than the stimuli generated on the screens.

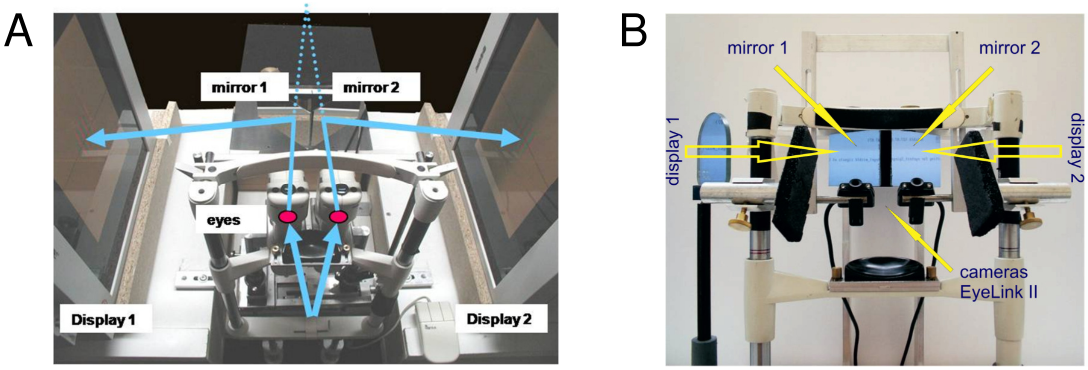

Figure 2.2. Schematic picture of mirror stereoscope showing position of monitors, mirrors, and cameras (EyeLink II) from top (A) and front (B). The photos reprinted with courtesy of Ifado.

Using mirror stereoscope, we subjectively measured fixation disparity and vergence step response and simultaneously recorded objectively the eye movements with an EyeLink II system at 500 Hz sampling rate.

Mirror stereoscope (based on principle described by Wheatstone[32]) requires precisely adjusted position of mirrors relative to the eyes and displays. LC shutter glasses are mechanically easier performed as mirror stereoscope. But even then, shutter glasses have several potential disadvantages: there still could be some flickering of the display even if refresh rate of the CRT is high; each eye may have a faint perception of the image intended to be visible only by the fellow eye because of the imperfect alternation of covering of the eyes[33]. To eliminate these problems, Jaschinski et al.[33] reduced contrast of the stimuli on a bright background. Thus, the stimuli were black on a white background with luminance of about 8 cd/m^2 measured through the activated LC shutter glasses and 33 cd/m^2 measured in the mirror stereoscope.

Jaschinski et al.[33] compared both techniques and observed high correlation between measurements obtained with both techniques. For measuring vergence step response, both techniques showed very similar results (for objectively obtained vergence velocity and vergence step response amplitude 400 ms after step stimulus onset) on the level of individual mean values. Even individual standard deviations were similar between shutter glasses and mirror stereoscope. Only for 1 degree vergence step stimulus, they observed that the vergence step response 400 ms after step stimulus onset tended to be more variable with shutter glasses. Based on this observation, they suggest to average results across all series of trials.

For fixation disparity measurements, the nonius bias and the fixation disparity showed also equivalent results in most participants. Only one participant showed an under-converging fixation disparity. They explained it as a result of disturbed perception of distance at the mirror stereoscope where one is not directly aware of the actual viewing distance. Thus, it affects the proximal vergence involvement in vergence response generation. They concluded that shutter glasses allow for more natural viewing conditions[33]. But still both techniques can be used and will give similar results to reflect inter-individual differences in fixation disparity and vergence step responses.

2.2. Stimuli

Stimuli contained peripheral (usually frame) and a central fusional target. For fixation disparity measurement, the fusion target was stationary and contained frame (300 min arc width and 230 min arc height; 12 min arc stroke width) with a central fusional stimulus XOX (30 min arc width and 30 min arc height (each symbol); 110 min arc all three symbols with separations; 12 min arc stroke width) (see Figure 2.3A).

Figure 2.3. The fusion stimulus for fixation disparity (A) and vergence step response (B) measurement. The fusion stimulus (A: XOX; B: a central fixation cross and a peripheral frame) was presented to both eyes, either at baseline stimulus level (corresponding to the viewing distance) or at additional disparity (convergent or divergent).

For vergence step response measurement, the fusion target contained frame

(300 min arc width x 230 min arc height; 12 min arc stroke width) with a central fixation cross (30 x 30 min arc; stroke width 6 min arc) (see Figure 2.3B). The disparity was introduced by relative lateral displacement of the images for the left and right eye.

The nonius lines (45 min arc long; 8 min arc stroke width; vertical separation of 50 min arc) were presented dichoptically by means of shutter glasses or mirror stereoscope: the upper line was visible only for the right eye and the lower line was visible only for the left eye.

2.3. Subjective measurements of fixation disparity using nonius technique

For measuring subjective fixation disparity, the slightly modified version of the adaptive psychometric procedure Best-PEST (Parameter Estimation by Sequential Testing)[34] was used. The nonius lines were flashed 30 times for 100 ms at 3 s intervals (see Figure 2.4), with varying amounts of nonius offset.

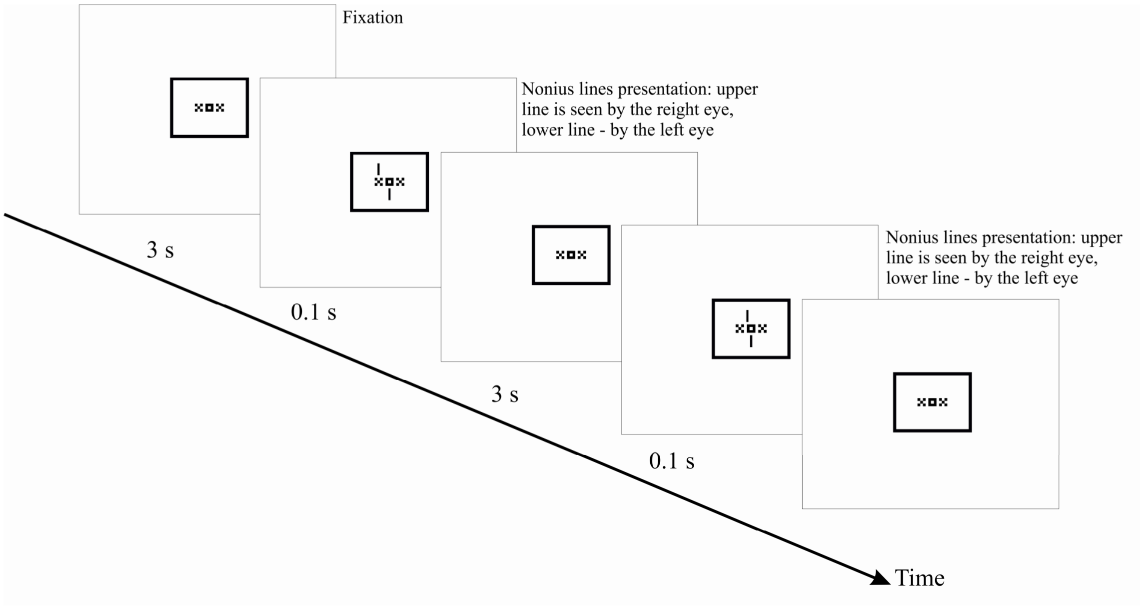

Figure 2.4. The sequence of the stimuli presentation to measure fixation disparity. The presentation started with fusion target containing frame and central symbols XOX. The nonius lines (upper line is seen by the right eye, lower line – by the left eye) were flashed 30 times for 100 ms at 3 s intervals with varying amounts of nonius offset, while the participants responded whether the upper nonius line was perceived left or right relative to the lower line.

The participants responded whether the upper nonius line was perceived left or right relative to the lower line by pushing the key of the mouse, either left or right, respectively.

When the lines were perceived as one above another (see Figure 2.5), participant had to choose either to push left or right key of the mouse. Thus, two-choice procedure was used.

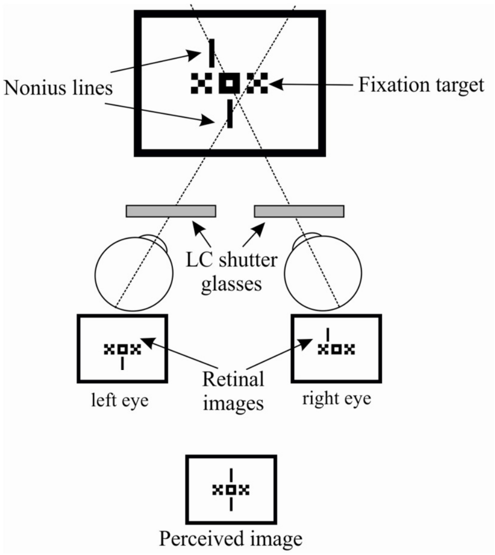

Figure 2.5. Schematic illustration of subjective evaluation of fixation disparity using LC shutter glasses: central (XOX) and peripheral (frame) fusion stimuli are visible for both eyes, while a pair of nonius lines are presented dichoptically, i.e. the upper line is only visible for the right eye and the lower line for the left eye (by means of liquid crystal (LC) shutter glasses in front of the eyes). In a case of eso fixation disparity (as in illustration), the upper nonius line has to be placed to the left of the lower nonius line, in order to be perceived collinear (opposite in the case of exo fixation disparity). Then, each nonius line is lying on the principle visual direction that determines the direction "straight ahead" of each eye. The fixation disparity is the visual angle corresponding to the resulting physical nonius offset.

We determined the nonius offset d required for subjective alignment, which allows calculation of fixation disparity (FD):

$$FD = 2 * \arctan((d/2 + PD/2)/s) - 2 * \arctan((PD/2)/s) \qquad \text{Eq. 2.1}$$

with the individual inter-pupillary distance PD and the viewing distance s. Thus, fixation disparity of zero means a precise vergence to the baseline stimulus.

In the slightly modified version of the adaptive psychometric procedure Best-PEST[34], the physical nonius offset presented in each trial[*] is an estimation of subjective alignment based on all previous trials (see Figure 2.6). We ignored the first 10 trials (during which the

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[*] One trial is one presentation of nonius lines.

adaptation procedure approaches the individual results) and took the mean of the remaining 20 trials as average vergence state of a run.

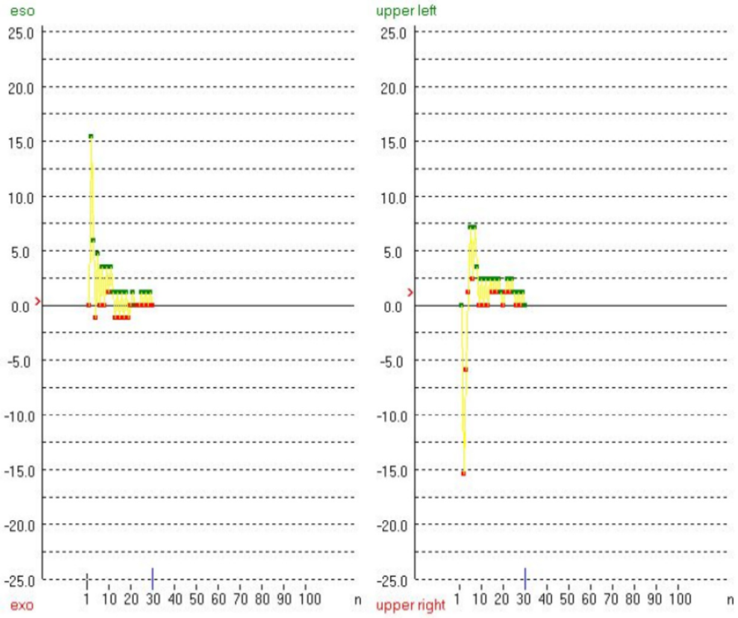

Figure 2.6. Illustration of data analyses for fixation disparity using the slightly modified version of the adaptive psychometric procedure Best-PEST[34]. Estimation of fixation disparity (min arc) and nonius bias (min arc) is shown on the left side and on the right side, respectively. Green points marks answers "upper line to the left" and red points "upper line to the right". In this example, fixation disparity is about 0.5 min arc eso and nonius bias is about 1.5 min arc eso.

The 30 trials of measuring fixation disparity were randomly interleaved by 30 trials where the dichoptic separation of the nonius lines was not active, i.e., both eyes viewed the upper and lower nonius lines. This is not a measure of vergence but rather a measure of the nonius bias[28]. The run with all 60 trials took approximately 3 minutes.

2.4. Subjective estimation of vergence response using nonius technique

Dichoptic nonius lines were also used to estimate the vergence state at certain moment in time during the response to a disparity stimulus by flashing them at a defined delay after the onset of the disparity step stimulus. The dichoptic nonius lines were used as test stimuli for measuring the vergence state as they are not effective as stimulus for vergence since they cannot be fused and are presented for 100 ms which is shorter than the latency of vergence in moment in time when they are flashed. Further, the moment in time when the participant gives the response (left or right) has no effect in the result since the response always refers to a perception of the nonius offset that corresponds to the moment when the nonius lines have been presented.

The vergence response was estimated with nonius delays (0, 100, 200, 300, 400, and 1000 ms depending of the experiment performed) relative to the onset of the step stimulus (see Figure 2.7). At each nonius delays, we calculated the vergence response relative to the baseline stimulus using the physical nonius offset d (calculated from Eq. 2.1).

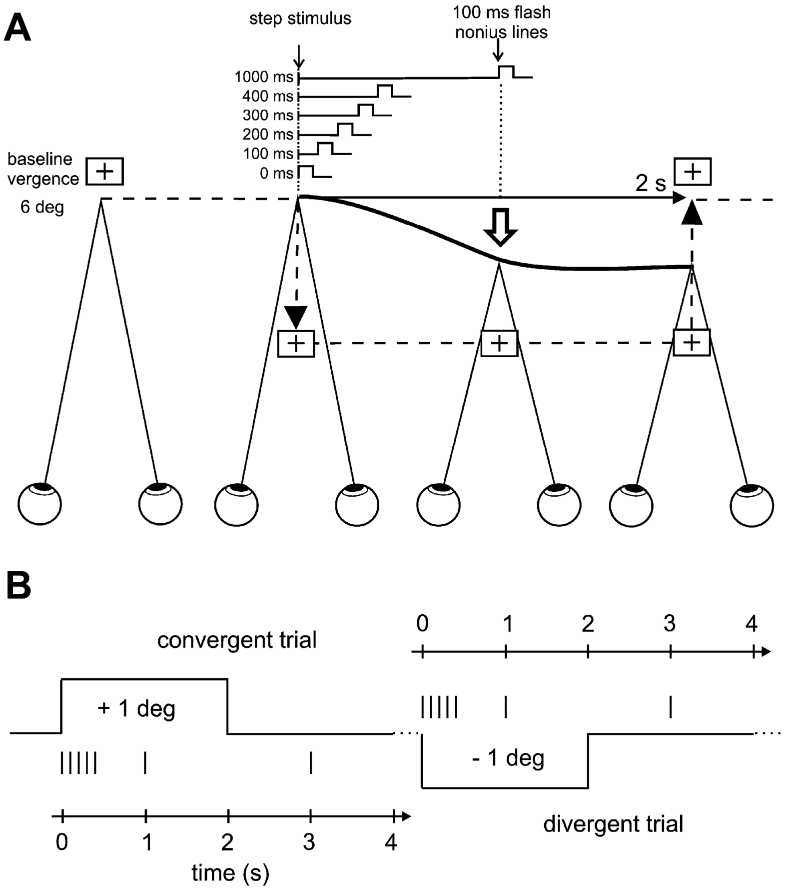

Figure 2.7. A. Time scheme of a single trial showing a convergence disparity step stimulus of 1 deg and the moments in time when the nonius lines were presented for a 60 cm viewing distance (baseline of 6 degree). In the upper right corner is presented the stimulus used also for static FD measurements. B. Sequence of one convergent and one divergent disparity step stimulus. Reprinted from Vision Research, 48(2), Jaschinski, W., Švede, A., Jainta, S. Relation between FD and the asymmetry between convergent and divergent disparity step responses, 253-263, Copyright (2008), with permission from Elsevier.

The adaptive test procedure used was similar as for the measurement of fixation disparity (see Figure 2.8). Separate runs were made with each amount of nonius delay. One run comprised 30 convergent and 30 divergent step stimuli (randomly interleaved). After each of these step stimuli, the baseline stimulus was presented again as a starting position for the next stimulus. We ignored the first 10 trials for each parameter (during which the adaptation procedure approaches the individual results) and took the mean of the remaining trials (20 trials for each parameter) as average vergence state of a run.

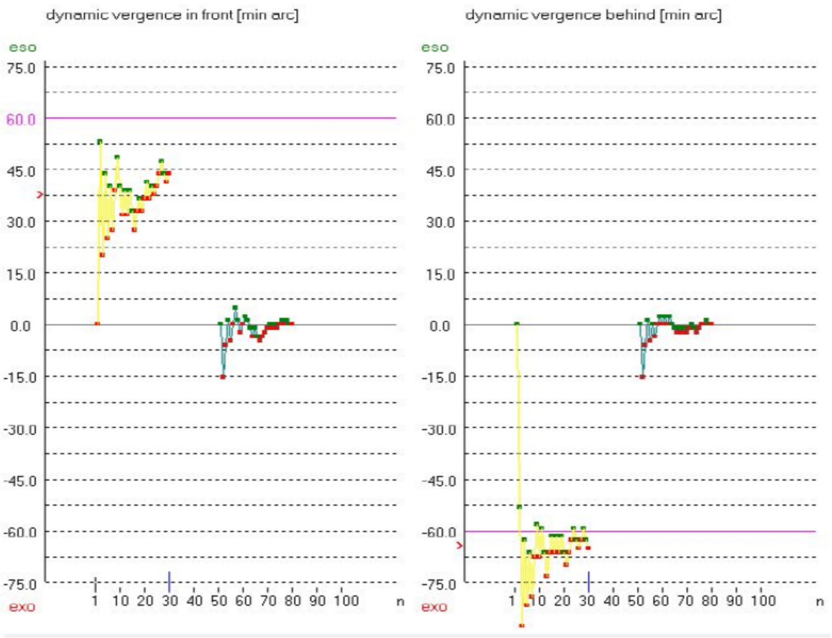

Figure 2.8. Illustration of data analyses for vergence response and baseline vergence evaluation using the slightly modified version of the adaptive psychometric procedure Best-PEST[34]. Estimation of convergence and divergence is shown on the left side and on the right side, respectively. Green points marks answers "upper line to the left" and red points "upper line to the right". In this example, the data points for the convergence response only reach 38 min arc, while the divergence response reaches 64 min arc. The baseline vergence is close to zero.

A sequence of a disparity step stimulus and a return to baseline included events showed in Figure 2.9. The experiment started with fusion target containing frame and a central fixation cross. A step disparity stimulus appeared after certain moment in time (T1, see Figure 2.9). After a fixed delay (for example, 100 ms as in Figure 2.9) from the disparity stimulus onset, the nonius lines appeared for 100 ms (participant gives the first response – vergence measurement). At the moment in time when the nonius lines were flashed, the participant had to respond whether the upper nonius line was perceived left or right relative to the lower line by pushing the key of the mouse, either left or right, respectively. When the lines were perceived as one above another, participant had to choose either to push left or right key of the mouse.

2 s after the onset of the disparity stimulus, the stimulus returned to baseline vergence and 1 s later the nonius lines were presented again (participant gives the second response – baseline vergence measurement). Baseline vergence (BV) evaluation was included to measure whether the previous response in the convergent or divergent direction had declined before the next step stimulus was presented and to calculate the effective amount of step stimulus that depends on the vergence state assumed before a step. Each run comprised two such measurements of baseline vergence: one after convergent and one after divergent step responses (see Figure 2.9).

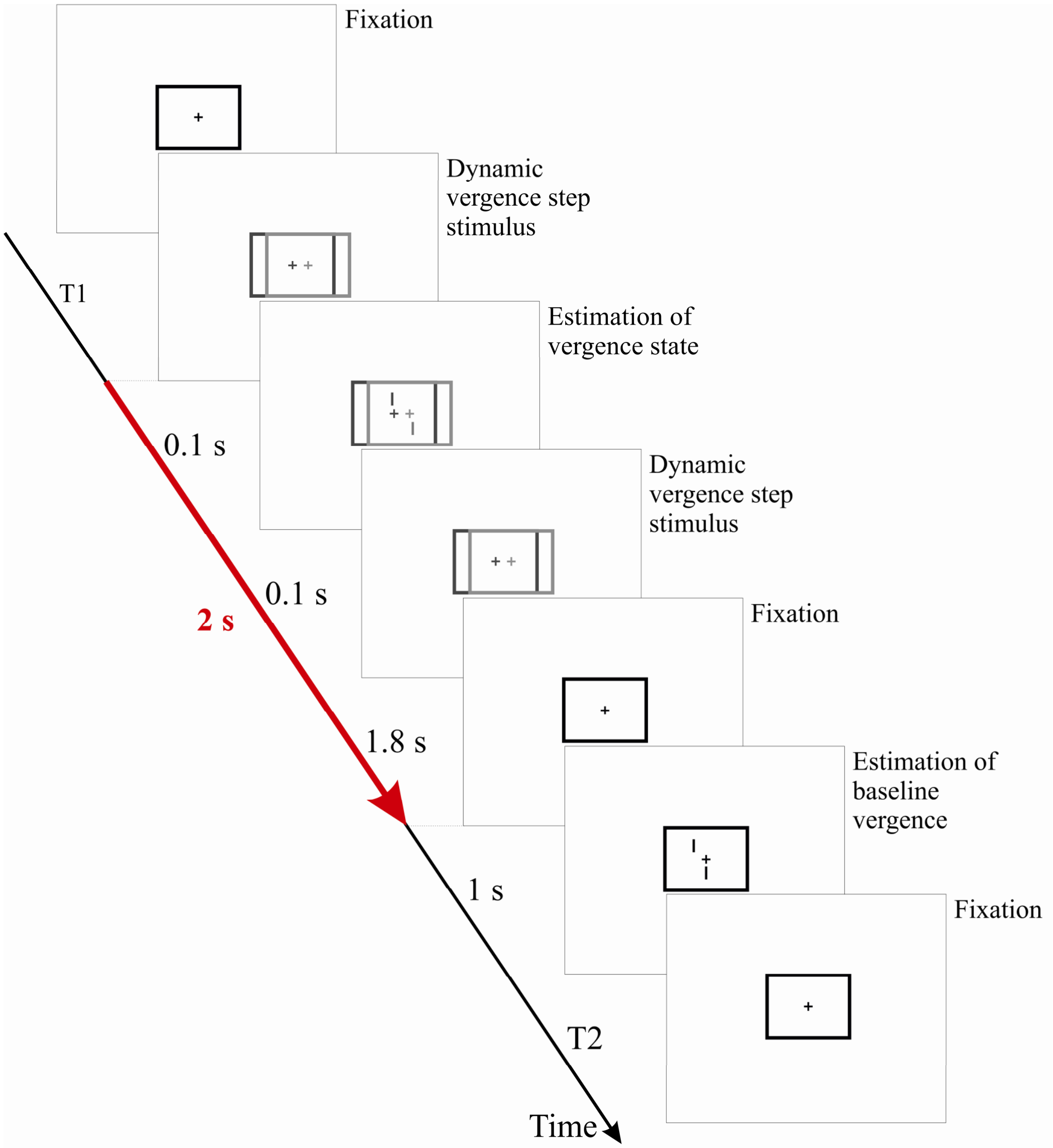

Figure 2.9. The sequence of the stimuli presentation to evaluate vergence response. The time (T1 + T2 + 1 s) between two disparity steps varied randomly in the range of 2.1-3.0 s.

The time between two disparity steps varied randomly in the range of 2.1-3.0 s, so that participants were uncertain about the direction and the moment of onset of the stimulus[35]. Thus, prediction, which could influence the dynamic processes of vergence step response as latency, maximal velocity and declining of the vergence response after stimulus is returned to baseline vergence position, was significantly reduced. One run with 60 sequences (30 convergent and 30 divergent; 120 trials) took about 5 min for each amount of nonius delay for subjective evaluation of vergence step response and about 6 min in combination with objective estimation of eye movements (because of calibration procedure).

2.5. Objective measurement of vergence step response using eye tracker

During the complete subjective test procedure (in Experiment III), eye movements were recorded with the video-based EyeLink II (SR Research Ltd, Osgoode, ON, Canada). Cameras were fixed to the head rest (see Figure 2.2), thus we did not use the helmet to mount the cameras nor the EyeLink compensation of head movements. Despite the high physical precision of the EyeLink system, its practical reliability is limited by the stability of the head position. Therefore the head of the participant was stabilized with a chin and forehead rest, pads for the cheeks, and a headband to minimize artifacts due to possible lateral and oblique head movements. We did not use a bite bar.

Both eyes were tracked simultaneously (500 Hz binocular monitoring). No participant wore glasses in order to avoid artifacts due to reflections. The dark pupil system tracks the centre of the pupil by an algorithm similar to a centroid calculation with a theoretical noise-limited resolution of 0.01 degree (0.6 min arc) and velocity noise of less than 3°/s for two-dimensional eye-tracking (details provided by SR Research Ltd, Osgoode ON, Canada).

The calibration procedure was similar as described by Jainta et al.[31]. Instead of the original EyeLink II calibration mode, we performed the following two-step purpose-made calibration: the first calibration was not made at the beginning of a run, but after the first 20 sequences (10 convergent and 10 divergent) evaluating vergence step response and after first 20 trials (of the total of 60 trials) evaluating fixation disparity; the second calibration was performed at the end of a run. Data were analyzed based on the average of these two calibrations for each run.

We used a 2-dimensional 9-point monocular (each eye separately) calibration to transform the screen coordinates into eye position coordinates; the calibration coefficients were calculated with a multivariate regression. Monocular presentations for the right and left eye were randomly interleaved. During calibration procedure, participants were requested to avoid blinking and to carefully fixate calibration targets that appeared for 1000 ms randomly at the screen centre or at horizontal and vertical displacements of 3.0 degree with 100 ms temporal gaps. Compared to the calibration range specified by the manufacturer (30 degrees of visual area), our calibration covered only 6 degrees of visual angle, but still included the angular area of the present vergence stimuli. In order to draw attention to the calibration targets and to facilitate exact fixation, the diameter of the spot initially subtended 1 degree and shrank immediately during 1000 ms to a remaining cross of 8.1 x 8.1 min arc (stroke width: 2.7 min arc). The remaining cross was visible for additional 400 ms during which calibration data were stored. These dynamic targets did not induce disturbing afterimages, since they were presented on a bright background. Jainta et al.[31] observed highly linear calibration curve, thus confirming the calibration procedure as adequate for such experiments.

2.5.1. Calculation of objective vergence step response

To calculate vergence step response from objective data, we used the horizontal raw within data epochs starting from 500 ms before stimulus appearance (pre trigger) and ending 1500 ms after stimulus appearance (the length of epoch was 2000 ms). Additionally, for estimation of objective baseline vergence, we used the period starting at 1100 ms and ending at 800 ms before stimulus were presented. Epochs containing artifacts were excluded from further analyze. The main artifact was blinking and extreme version eye movements within each epoch. Epochs containing blinks (velocity of movement bigger than 40°/sec) in the period between 100 ms and 600 ms after stimulus onset were discarded. Epochs with blinks outside this period were not excluded, but these missing data were linearly interpolated. If the mean vergence within the last 50 ms of a step response (in time moment from 1000 ms till 1050 ms) deviated by more than 20% from the established mean individual sample response, this epoch was excluded from further analyze. The vergence response was calculated from each epoch as a difference between the positions of the two eyes relative to objective baseline.

This procedures have two advantages to reduce measurement error: (1) the averaging across many trials, runs, and calibrations minimizes the variability due to these factors, and (2) since vergence velocity is a relative change within a short period, we reduce drift artifacts, e.g. due to residual head instability. Previous research[31] confirmed these procedures to determine individual vergence velocity. Further, previous experiments with similar methodology[14] showed that vergence changes (after saccades) in the small range of only 20 min arc could be measured reliably with a test-retest correlation of 0.88.

2.5.2. Calculation of objective fixation disparity

To calculate fixation disparity from objective data, we used similar proceedings as for the vergence step response calculation. Data were extracted during a 500 ms period from 200 ms before to 300 ms after appearance of nonius lines. Additionally to the processing of artifacts as described for vergence step response, we excluded epochs if the standard deviation exceeded 30 min arc within one epoch. Objective fixation disparity was calculated from each epoch as a difference between the positions of the two eyes relative to the theoretical vergence angle. To calculate the final fixation disparity, the total average value across all nonius presentations of all available runs was calculated. This calculation takes into account the variation of inaccuracy of calibrations and the variation of repetition of measurements.

2.5.3. Calculation of heterophoria

During monocular calibrations for Experiment III, one eye fixated the calibration target, and the other eye was not provided with a target. Therefore, the binocular recordings showed a vergence angle without a fusion stimulus, a condition known as heterophoria[14]. Two heterophoria measurements were taken from each central calibration point, one while each eye was fixating. Because of the high correlation of both measures ($r = 0.99$), they were averaged. Individual heterophoria was described as exophoria (uncrossed visual axes; minus sign), esophoria (crossed visual axes; plus sign) or orthophoria (visual axes intersect perfectly at the visual target – zero heterophoria). Therefore, heterophoria was obtained at the same viewing distance (it was 60 cm for Experiment III) and in the same experimental conditions as vergence velocity and FD.

2.6. Dark vergence measurements

Dark vergence was also measured with an adaptive psychometric procedure, Best-PEST[34] (similarly as fixation disparity). To present dichoptical separation, we used LC shutter glasses. A small red square (17 min arc width x 17 min arc height; seen with the right eye) and a red line (155 min arc length; 3 min arc stroke width; seen with the left eye) were flashed for 100 ms on a dark screen at a 100 cm viewing distance in a completely dark room. We used a red light for stimulus presentation because with red light the cross-talk of the LC shutter glasses between the two eyes is eliminated, e.g. the right eye will not perceive a residual image shown to the left eye. Testing was started after brief adaptation after lighting was switched off in a windowless room. The average of two measurements was taken for further analyses. Both measurements took about 5 min.

3. Relation between fixation disparity and the asymmetry between convergent and divergent disparity step responses (Experiment I)

3.1. Purpose of the Experiment I

The purpose of Experiment I was to evaluate the reliability of the nonius method used to subjectively measure fixation disparity and vergence response at 60 cm viewing distance. Additionaly it tests a possible correlation between the fixation disparity for a stationary fusion stimulus at a 60 cm viewing distance and the convergent-divergent asymmetry of vergence dynamics for a disparity step stimulus of 60 min arc (1º). This correlation was used to determine the amount of inter-individual variance in fixation disparity that can be explained by individual differences in the asymmetry of vergence dynamics as predicted by the neural network model of Patel et. al.[22-23]

3.2. Participants I

We tested 16 participants (age 20-44 years, mean age – 25 years; visual acuity 1.0 or better (in decimal units) with correction (if needed, eleven participants wore refractive corrections during testing) at the test viewing distance; with binocular single vision and stereopsis).

Group of 16 participants were formed of two sub-samples:

- Eight participants were tested in the Department of Optometry and Vision Science, University of Latvia (Riga, Latvia). They represented a random sample with respect to fixation disparity. They were labeled with letter “R” (R1 – R8).
- Eight participants were tested in the Leibniz-Institut für Arbeitsforschung an der TU Dortmund in Dortmund (Germany). These participants were chosen from a large pool of participants to have a larger amount of fixation disparity in the eso and exo direction. They were labeled with letter “D” (D1 – D8).

Additional choice of participants in the Dortmund sub-sample was made since many participants with a fixation disparity close to zero (as seen in the random sample) do not allow a critical testing of the hypothesis whether the direction of fixation disparity is related to the asymmetry in vergence dynamics. Although most participants in the Dortmund sub-sample had larger fixation disparities, they had no binocular vision problems. They all had:

- stable binocular single vision,
- good stereovision with stereovision threshold (mean ± SD) of 36 ± 16 sec arc

(range 15 – 60 sec arc) for crossed binocular disparity and 40 ± 18 sec arc (range 15-60 sec arc) for uncrossed binocular disparity in the TNO-stereo test,

- dark vergence of 0.96 ± 0.66 meter angle (range 0.5-2.4 meter angle). These results correspond to the mean dark vergence findings described by Jaschinski[27]. They found 0.92 ± 0.46 meter angle (mean ± SD) large dark vergence in a group of 40 participants using similar method as in this experiment.

The experiments were undertaken with the understanding and written consent of all 16 participants. The procedures of the present study were approved by the Ethics Review of the Leibniz-Institut für Arbeitsforschung an der TU Dortmund and followed the tenets of the Declaration of Helsinki.

3.3. Experimental design I

All participants took part in two repeated sessions on separate days, in order to evaluate the test-retest reliability. Each session comprised subjective fixation disparity measurement at 60 cm viewing distance and subjective vergence disparity step response measurements for six nonius delays (0, 100, 200, 300, 400, and 1000 ms), including both convergent and divergent directions. The order of the six runs for the vergence response measurement was randomly varied. Subjective estimation of dynamic vergence response was made with step disparity stimuli of 60 min arc (1º) at 60 cm viewing distance (baseline vergence of about 6º) which induced an accommodative stimulus of 1.67 D.

The whole experiment was run in a separate room with dim lighting. After two or three runs participants had a rest of about 5 min. Thus, each session took about 40 min, including rests. Periods of near vision did not occur, thus did not induce vergence adaptation. For data analyses, we used statistics available on R software, Microsoft Excel, Origin, and MedCalc.

3.4. Results I

3.4.1. Reliability of FD and vergence response measurements

We compared the results of two sessions made on separate days, in order to evaluate the repeatability of our method. The test-retest correlation resulted in $r = 0.90$ ($p < 0.0001$, one-tailed) for fixation disparity (see Figure 3.1A). In ideal situation, the slope of the regression line should be 1.0. The analyses of regression showed slope coefficient of 1.02 ± 0.13 ($p < 0.0001$; 95% of confidence interval CI = ±0.29), that is not significantly different from 1.0. The y-intercept was -0.81 ± 0.54. taking into account the results of regression analyses and the confidence intervals ($p > 0.05$; 95% confidence interval CI = ±1.16) y-intercept is not significantly different from zero. As a further indicator of the reliability, we used the standard deviation of the difference between repeated measurements[36]. This standard deviation was 2.0 min arc and the coefficient of repeatability was 3.9 for FD (see Figure 3.1B).

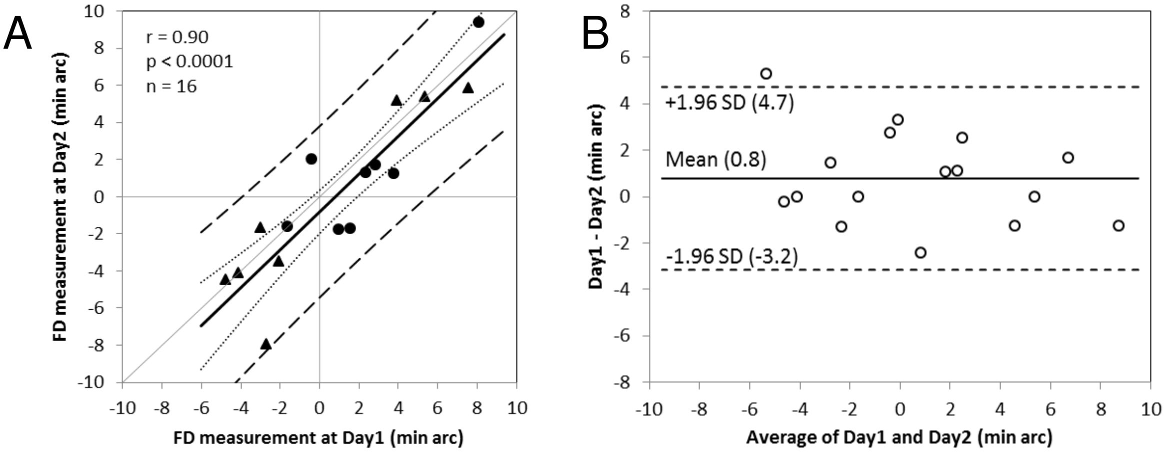

Figure 3.1. A. The test-retest correlation for fixation disparity, measured at two different sessions (Day1 and Day2). The correlation was r = 0.90 (p < 0.0001, one-tailed) for the sample group of 16 participants. Circles and triangles indicate participants of Riga and Dortmund sub-sample, respectively. B. The Bland-Altman plot for fixation disparity, measured at two different sessions (Day1 and Day2). The coefficient of repeatability was 3.9 for the sample group of 16 participants. Continuous line shows the arithmetic mean, and broken lines show the upper and lower limits of the difference between repeated measurements of fixation disparity. Positive values refer to eso fixation disparity and negative values – to exo fixation disparity.

For the vergence step responses, the test-retest correlation (median across all conditions tested) was r = 0.94 (range 0.74-0.99; p < 0.001, one-tailed) (see Figure 3.2A). The analyses of regressions, as well as the standard deviations of the difference between repeated measurements and the coefficients of repeatability are given in Table 3.1 (see also Figure 3.2B).

For baseline vergence, the test-retest correlation (median across all conditions tested) was r = 0.86 (range 0.79-0.92; p < 0.001, one-tailed) (see Figure 3.3A). The analyses of regressions, as well as the standard deviations of the difference between repeated measurements and the coefficients of repeatability are given in Table 3.2 (see Figure 3.3B).

The Bland-Altman analyses showed absolute systematic error of the method, but no influence of the magnitude of the measurements for neither of parameters. The variability within participants were much smaller compared to the variability between participants (see Figures 3.1B-3.3B).

Table 3.1

Test-retest correlation, slope of regression line, y-intercept of regression line, standard deviation of the difference between the two repeated measurements, and coefficient of repeatability for the vergence step responses (at each amount of the nonius delay).

	Convergent step response					Divergent step response				
Nonius delay (ms)	Test-retest correlation (r)	Slope of regression line ± standard error	Y-intercept of regression line ± standard error	SD of the difference (min arc)	Coefficient of repeatability	Test-retest correlation (r)	Slope of regression line ± standard error	Y-intercept of regression line ± standard error	SD of the difference (min arc)	Coefficient of repeatability
0	0.74	0.78 ± 0.19	-0.3 ± 4.1	13	26	0.82	0.77 ± 0.14	-2.2 ± 2.5	11	21
100	0.91	0.87 ± 0.10	-1.0 ± 2.3	8	15	0.93	0.86 ± 0.09	-2.0 ± 1.9	7	14
200	0.85	0.97 ± 0.16	-2.9 ± 4.6	12	23	0.95	0.88 ± 0.08	-5.5 ± 2.5	8	15
300	0.82	1.06 ± 0.20	-7.6 ± 6.5	15	29	0.99	0.98 ± 0.03	-3.5 ± 1.6	3	7
400	0.96	0.87 ± 0.07	2.6 ± 2.5	8	16	0.96	0.97 ± 0.07	-0.6 ± 3.6	7	14
1000	0.97	0.99 ± 0.07	0.1 ± 2.8	7	14	0.97	1.03 ± 0.07	3.7 ± 3.9	5	9

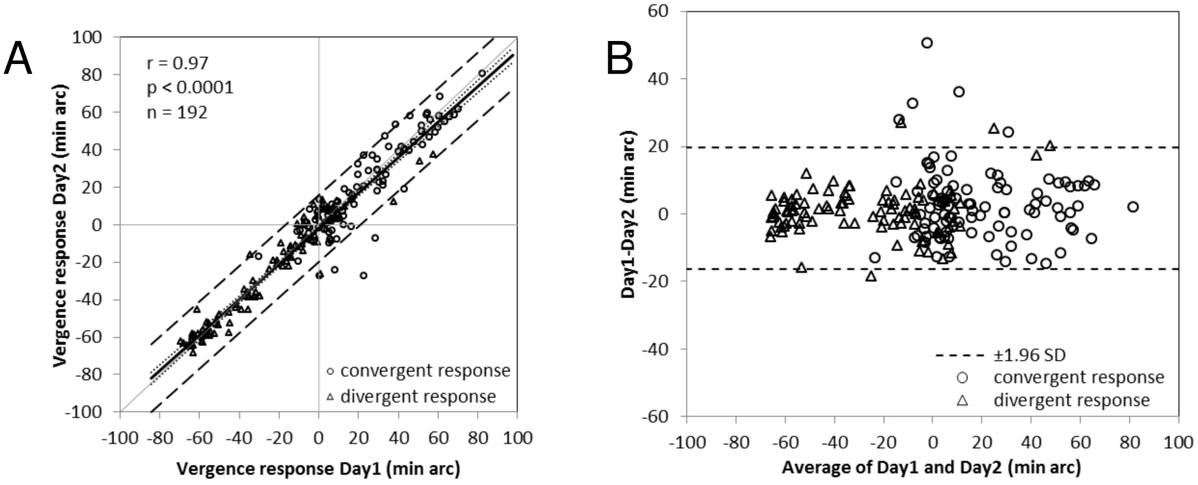

Figure 3.2. A. The test-retest correlation for vergence step responses, measured at two different sessions (Day1 and Day2). The correlation (for all data of convergent and divergent step responeses) was r = 0.97 (p < 0.0001, one-tailed). The slope of regression line was 0.95 ± 0.02 (p < 0.0001; 95% of confidence interval CI = ±0.04). B. The Bland-Altman plot for vergence step responses, measured at two different sessions (Day1 and Day2). The coefficient of repeatability was 18.0 for all vergence step response data (convergent and divergent). Broken lines show the upper and lower limits of the difference between repeated measurements. Circles and triangles indicate convergent and divergent responses, respectively.

Table 3.2

Test-retest correlation, slope of regression line, y-intercept of regression line, standard deviation of the difference between the two repeated measurements, and coefficient of repeatability for baseline vergence (at each amount of the nonius delay).

	Baseline vergence (after convergent step response)					Baseline vergence (after divergent step response)				
Nonius delay (ms)	Test-retest correlation (r)	Slope of regression line ± standard error	Y-intercept of regression line ± standard error	SD of the difference (min arc)	Coefficient of repeatability	Test-retest correlation (r)	Slope of regression line ± standard error	Y-intercept of regression line ± standard error	SD of the difference (min arc)	Coefficient of repeatability
0	0.79	0.89 ± 0.19	0.1 ± 1.4	5	10	0.87	1.02 ± 0.16	0.2 ± 1.2	4	9
100	0.92	0.91 ± 0.10	0.0 ± 0.9	3	6.	0.84	0.92 ± 0.16	-1.6 ± 1.4	5	11
200	0.83	0.83 ± 0.15	0.1 ± 1.4	6	12	0.82	0.98 ± 0.18	-0.5 ±1.5	6	11
300	0.89	1.01 ± 0.14	0.5 ± 1.1	4	8	0.83	1.04 ± 0.19	-2.7 ± 1.6	6	12
400	0.87	0.65 ± 0.10	2.6 ± 1.2	6	12	0.91	0.67 ± 0.08	2.1 ± 1.3	7	14
1000	0.90	0.95 ± 0.12	0.6 ± 0.9	3	7	0.84	0.95 ± 0.17	0.4 ± 1.1	4	9

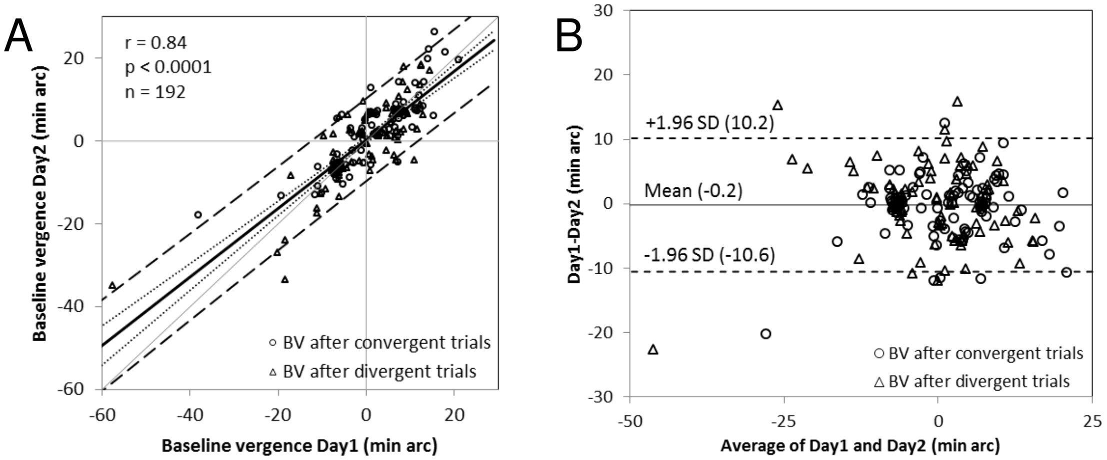

Figure 3.3. A. The test-retest correlation for baseline vergence, measured at two different sessions (Day1 and Day2). The correlation was r = 0.84 ($p < 0.0001$, one-tailed). The slope of regression line was 0.83 ± 0.04 ($p < 0.0001$; 95% of confidence interval CI = ±0.08). Circles and triangles indicate baseline vergence after convergent and divergent trials, respectively. Positive values refer to over-convergence (eso), while negative values refer to under-convergence (exo) relative to convergence to the baseline stimulus. B. The Bland-Altman plot for baseline vergence, measured at two different sessions (Day1 and Day2). The coefficient of repeatability was 10.4 (calculated for all data). Broken lines show the upper and lower limits of the difference between repeated measurements.

The test-retest correlations and Bland-Altman analyses confirm that psychophysical procedure used in the experiment provides stable measures of individual vergence performance (fixation disaprity, vergence step responses and baseline vergence). To reduce residual intra-individual variability, we averaged the results of two sessions (made on separate days) for further analyses.

3.4.2. Description of vergence step response functions

Three typical response patterns were found in the sample of 14 participants (see Figure 3.4-3.5). Five participants (2 from Riga sub-sample and 3 from Dortmund sub-sample) show an ordinary response: after same latency, a steep phase of the response was observed and, later, the response saturates and a final level was reached. Three participants (R1, R8 and D3) showed a steep phase of the response for nonius delays in the range of 100-400 ms, saturation of the response at about 400 ms nonius delay reaching final level near the stimulus amplitude of 60 min arc for both vergence step stimulus – convergent and divergent (see Figure 3.4A, B). Two participants (D4 and D6) showed a little bit weaker response pattern in one of directions. A full response was observed only for convergent step stimuli in participat D4 and for divergent step stimuli in participant D6. The vergence step reponse in the other direction (divergent for participant D4 and convergent for participant D6) was weaker and reached only the half of the stimulus amplitude (about 30 min arc) (see Figure 3.4C, D).

Eight participants (4 from Riga and 4 from Dortmund sub sample; R3, R4, R5, R7, D1, D5, D7, D8) showed virtually no convergent response, but an ordinary divergent response (see Figure 3.4E). One participant from Riga sub-sample (R2) showed opposite patern – virtually no divergent response, but an ordinary convergent response (see Figure 3.4F).

The two remaining participants (R6 and D2) showed response patterns (see Figure 3.5) that differed considerably from those described before. It is hard to evaluate and to explain the vergence responses of those two participants. Participant R6 could have no convergence response, but good divergence response if we consider only the change of vergence response from initial position (at 0 ms nonius delay). Convergence response did not changed significantly (change was about 7 ± 17 min arc from initial position) at any nonius delays, but there were significant divergence response changes (change was about 70 ± 17 min arc from initial position). But, we could describe this response also as a very fast and strong convergence and also good but weaker divergence. Similarly, it seems participant D2 has good and fast convergence, but no divergence.

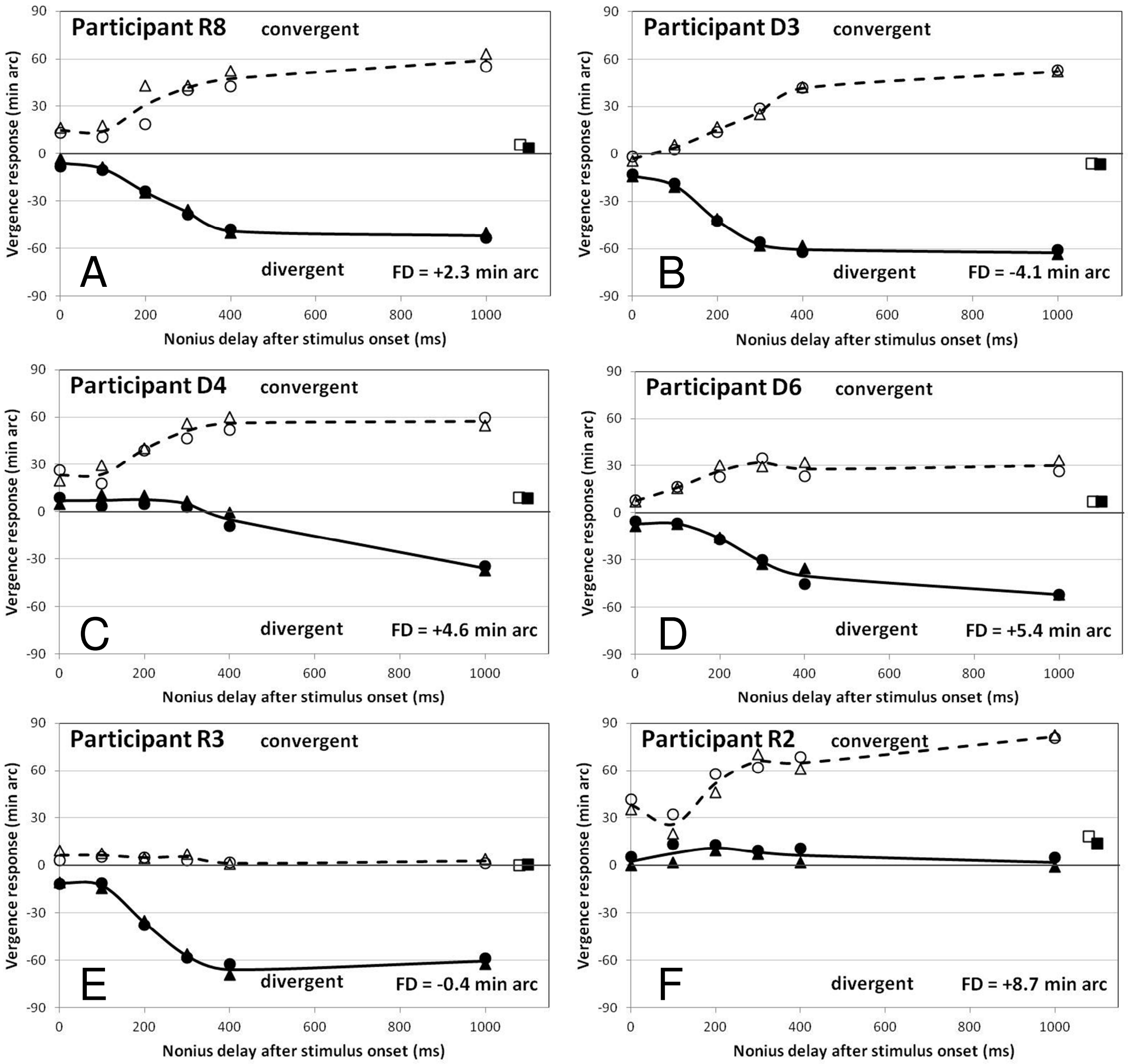

Figure 3.4. Examples of vergence step responses in six participants. A and B. Two participants (R8 and D3) showing a steep phase of the response for nonius delays in the range of 100-400 ms, saturation of the response at about 400 ms nonius delay reaching final level near the stimulus amplitude of 60 min arc. C and D. Two participants (D4 and D6) showing weaker response pattern in one of the directions (divergent for participant D4 and convergent for participant D6) reaching only the half of the stimulus amplitude (about 30 min arc). E. One participant (R3) showing virtually no convergent response, but an ordinary divergent response. F. One participant (R2) showing virtually no divergent response, but an ordinary convergent response. Positive and negative response values refer to convergent and divergent states (corresponding to the viewing distance of 60 cm). Responses for convergent and divergent step stimuli (open and closed symbols, respectively) are plotted as a function of the amount of nonius delay (0, 100, 200, 300, 400, and 1000 ms) after the disparity step stimulus. The pairs of data points (triangles and circles) refer to the first and second session to illustrate the reliability; the lines show the mean values. The two data points beyond 1000 ms indicate the vergence state reached 1000 ms after the disparity stimulus was switched off and replaced by the baseline fusion

stimulus; these measurements of baseline vergence states are shown separately for convergent and divergent trials (open and closed squares), but averaged across the six amounts of nonius offset and across test and retest data. The mean of these two baseline vergence states estimate the initial vergence state, assumed before onset of the following disparity stimulus within the series of responses. In the right lower corner, the magnitude of fixation disparity (FD; mean of two sessions) is given. The labels of the prticipants "R" and "D" mean that they belong to the sub-sample tested in Riga or Dortmund, respectively.

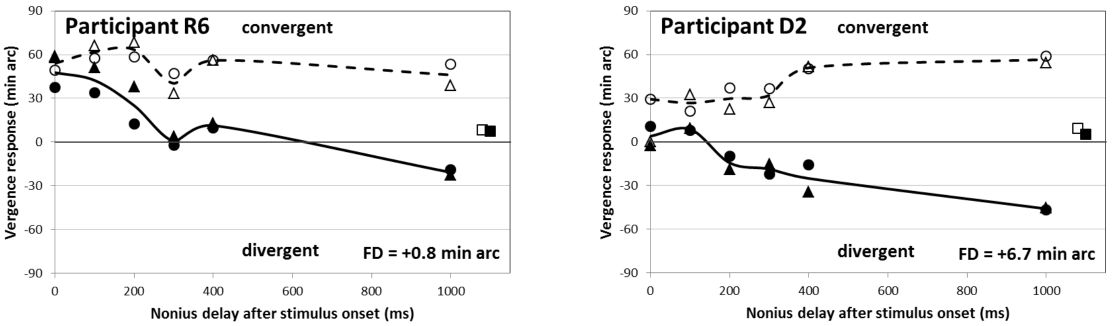

Figure 3.5. Disparity vergence step responses in two participants (R6 and D2) showing considerably different pattern. Positive and negative response values refer to convergent and divergent states (corresponding to the viewing distance of 60 cm). Responses for convergent and divergent step stimuli (open and closed symbols, respectively) are plotted as a function of the amount of nonius delay (0, 100, 200, 300, 400, and 1000 ms) after the disparity step stimulus. The pairs of data points (triangles and circles) refer to the first and second session to illustrate the reliability; the lines show the mean values. The two data points beyond 1000 ms indicate the vergence state reached 1000 ms after the disparity stimulus was switched off and replaced by the baseline fusion stimulus; these measurements of baseline vergence states are shown separately for convergent and divergent trials (open and closed squares), but averaged across the six amounts of nonius offset and across test and retest data. The mean of these two baseline vergence states estimate the initial vergence state, assumed before onset of the following disparity stimulus within the series of responses. In the right lower corner the magnitude of fixation disparity (FD; mean of two sessions) is given. The labels of the participants "R" and "D" mean that they belong to the sub-sample tested in Riga or Dortmund, respectively.

Convergence response was about 52 min arc and about 30 min arc already at the 0 ms nonius delay for particiapant R6 and D2, respectively. We have to consider that a nonius delay of 0 ms means that the nonius onset was at the same moment in time as the disparity step stimulus onset. However, the moment in time when the vergence response was measured subjectively by the perception of nonius lines may be some unknown period later due to a delay in perception. Thus, we cannot assume that both participants had so big vergence shift at the moment of disparity stimulus onset. They just seem having a much faster initial convergent response than all other participants. On the first view, this pattern of result seems implausible. However, it was reliable since it was observed in a similar way in both sessions.

For a divergent response, participant R6 had the initial response (at 0 ms nonius delay) in the convergent direction. Participant D2 started divergent response at the level close to the baseline vergence similar as it was observed for other participants. It is possible that participant R6 has so strong response in convergent direction that even with divergent stimuli a convergent response was initiated in the moment of the disruption of the fusion stimulus (at 0 ms nonius delay). The response changed into appropriate divergent direction only later.

For participant R6 there could be one more explanation related to his accommodation behaviour. This participant wore a full correction of myopia only during testing (after a short addaptation period), but not in a everyday vision. As the testing was done at close distance (60 cm) where stronger accommodation response is needed if full accommodation correction is worn, he might have exerted a rather strong amount of accommodation during the test, which could have induced a stronger convergence response. Thus, changing the vergence step stimulus from initial position, there was no need for additional convergence change but stronger divergence change.

Similar explanations were not possible to find for participant D2. Therefore, we analyzed the further results without and with those two participants.

Generally, however, it is possible to detect different individual patterns of vergence response using subjective method. Only for some participants, it would not be possible to explain the subjectively observed vergence response. It could be helpful to make addition measurements by changing accommodation stimulus and also to use some objective methods to understand the vergence movement observed during subjective measurements.

3.4.3. Baseline vergence

Since we used the psychophysical method for vergence response measurement, participants performed 40 vergence step responses (and corresponding backward steps) within a run. Thus, the question arises to what extent the eyes had returned to the baseline vergence state when the next stimulus was presented. To evaluate this, the nonius lines were presented 1 s after each disparity step stimulus was switched off and the baseline fusion stimulus was presented again (relative to a baseline vergence of approximatelly 6º taking into account individual variance in interpupilar distances of participants). We expected that the eyes tend towards the individual fixation disaprity (the vergence state obtained with stationary fusional stimulus).

As analysed in the previous section, there was good repeatability of baseline vergence measurements. ANOVA test showed no significant difference ($p > 0.05$) for baseline vergence measurements at different nonius delays neither for baseline vergence after convergent trials, nor after divergent trials. Thus, we could average baseline vergence between all nonius delays.

As seen in Figure 3.6, the baseline vergence of both the convergent and the divergent responses were highly correlated with fixation disparity ($r = 0.92$ and $r = 0.83$, respectively, $p < 0.0001$, $n = 16$).

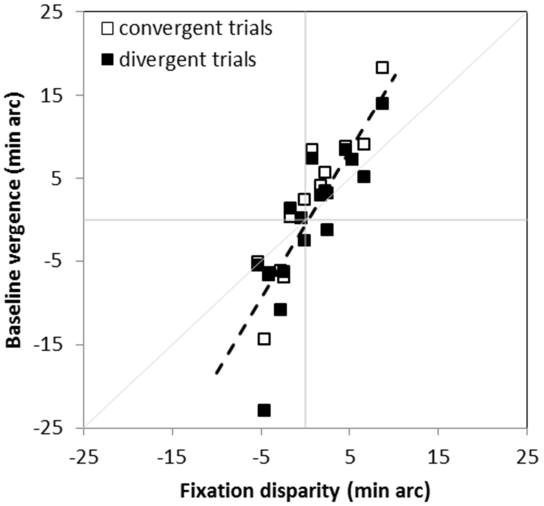

Figure 3.6. Relation between fixation disparity and baseline vergence measured after convergent and divergent trials (open and closed symbols, respectively) for the sample group of 16 participants. Positive values refer to over-convergence (eso), while negative values refer to under-convergence (exo). Baseline vergence states were significantly more positive (eso) after convergent than after divergnt trials. Each baseline measure was significantly correlated with fixation disparity ($r = 0.92$ and $r = 0.83$, respectively). The mean of both baseline vergence (BV) measures is related to fixation disparity (FD) following the regression equation $BV = -0.6 + 1.8\ FD$ (broken line); the y-intercept is not significantly different from zero (95% confidence interval CI = ±2.3), while the slope is significantly steeper than 1.0 (95% confidence interval CI = ±0.6).

However, the inter-individual range was larger for baseline vergence than for fixation disparity. This suggests that after convergent (divergent) responses participants with a large exo (eso) fixation disparity reached an exo (eso) baseline vergence that was larger than the amount of fixation disparity.

It appears that the baseline vergence tends to be more eso after convergent responses (mean ± SD = 2 ± 8 min arc for n = 16 and 1 ± 8 min arc for n = 14) than after divergent responses (-0 ± 9 min arc for n = 16 and -1 ± 9 min arc for n = 14). This difference was statistically significant independently of the fact whether we include the results of all 16 participants (t = 3.21, p = 0.006, df = 15, two-tailed), or we exclude the results of participant R6 and D2 (t = 2.80, p = 0.01, df = 14, two-tailed). If we looeked on the difference between both means (2.2 min arc for n = 16 and 2.1 min arc for n = 14), it was negligible relative to the large range of inter-individual differences (32.6 min arc for baseline vergence after convergent trials and 37.0 min arc for baseline vergence after convergent trials). Thus, the baseline vergence state was only marginally affected by the direction of the previous step response and we can average those two baseline vergence measurements for further analyses.

3.4.4. Relation between fixation disparity and the convergent-divergent asymmetry in vergence dynamic

To test the hypothesis whether fixation disparity is proportional to the convergent-divergent asymmetry in vergence dynamic, we used predictor that should be proportional to fixation disaprity as suggested by Patel et al.[23] (see Eq. 3.1):

$$FD_{pre} \sim \frac{(\surd(V_{conv}/(SV - BV)) - \surd(V_{div}/(SV + BV)))}{(\surd(V_{conv}/(SV - BV)) + \surd(V_{div}/(SV + BV)))} \qquad \text{Eq. 3.1}$$

where vergence gain factors are represented by convergence and divergent velocities (V_{conv}, V_{div}). The vergence velocities are corrected by weighting factors to account for the fact the vergence movement did not start at a theoretical baseline vergence, but at an individual baseline vergence (BV). As the result of this, the individual disparity vergence step stimulus was not 60 min arc, but (60 – BV) for convergent trial and (60 + BV) for divergent trials. As described previously, we averaged all baseline vergence measurements across convergent and divergent trials (two sessions and 6 nonius delays).

The vergence velocity was estimated from the subjective responses in the range of nonius delays from 100 to 400 ms. For each of the three 100 ms intervals (100 vs. 200 ms, 200 ms vs. 300 ms, and 300 vs. 400 ms), we calculated a corresponding change in vergence and chosed the maximal value as a subjective estimation of maximal vergence velocity. As shown by Jainta et al.[31], subjectively estimated maximal vergence velocity was highly correlated with objective estimation of vergence velocity.

For two particiants (R6 and D2), the estimation of vergence velocity based on nonius delays of 100, 200, 300, and 400 ms was not appropriate since a considerable change in vergence response occurred already in the very initial phase that cannot be sampled by the present subjective test procedure. Thus, we excluded those two participants from initial analyzes and used only data from 14 participants.

We found a high correlation (Pearson correlation coefficient $r = 0.71$, $p = 0.004$, two-tailed, $n = 14$) between predictor of fixation disaprity and the measured fixation disaprity (see Figure 3.7). Accordingly, similar correlation appeared in both sub-samples. We found Kendall rank correlation coefficient $\tau = 0.71$ ($p = 0.02$, two-tailed, $n = 7$) in Riga sub-sample (7 closed circles in Figure 3.7) and $\tau = 0.81$ ($p = 0.01$, two-tailed, $n = 7$) in Dortmund sub-sample (7 closed triangles in Figure 3.7). Pearson correlation coefficient was even higher – $r = 0.95$ ($p = 0.001$, two-tailed, $n = 7$) and $r = 0.81$ ($p = 0.03$, two-tailed, $n = 7$) for Riga and Dortmund sub-samples, respectively. As seen in Figure 3.7, these correlations were influenced by the outliers in the direction of the hypothesis.

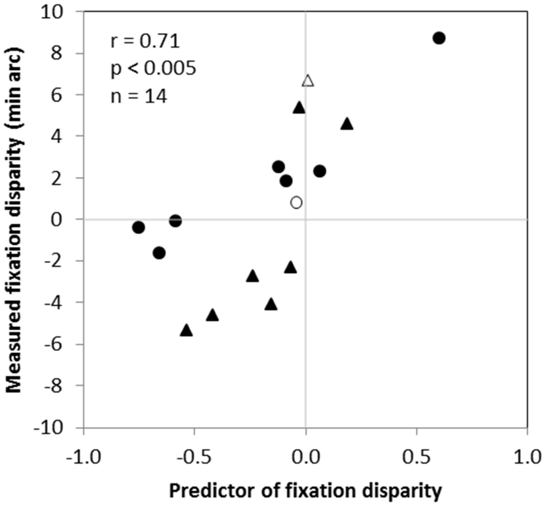

Figure 3.7. Correlation between measured fixation disparity and the predictor of fixation disparity following the neural network model of Patel et al.[23], i.e., FD_{pre}, Eq. 3.1. The correlation was $r = 0.71$ ($p < 0.005$; one-tailed) for the sample of 14 participants, where the estimation of vergence velocity was appropriate. If the remaining two participants (open symbols; R6 and D2) with a questionable subjective vergence velocity were included, the correlation was $r = 0.70$ ($p < 0.005$; two-tailed, $n = 16$). Circles and triangles indicate participants of Riga and Dortmund sub-sample, respectively.

As baseline vergence showed high correlation with measured fixation disparity (Pearson correlation coefficient $r = 0.88$, $p < 0.0001$, two-tailed, $n = 16$ and $r = 0.91$, $p < 0.0001$, two-tailed, $n = 14$, if results of baseline vergence were averaged between all vergence trials –

convergent and divergent), we additionally tested whether the prediction following equation 3.1 holds also for the baseline vergence. And we found significant correlation of 0.58 ($p = 0.03$, two-tailed, $n = 14$) as shown in Figure 3.8. Two participants we initially excluded from the analyzes (R6 and D2) did not significantly changed this correlation ($r = 0.60$, $p = 0.01$, $n = 16$).

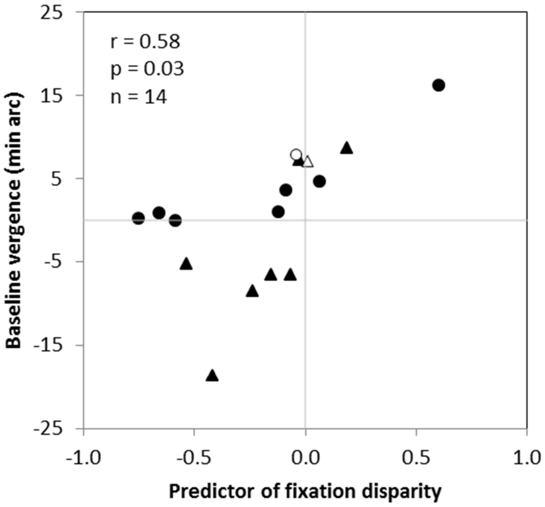

Figure 3.8. Correlation between baseline vergence and the predictor of fixation disparity following the neural network model of Patel et al.[23], i.e., FD_{pre}, Eq. 3.1. The correlation was $r = 0.58$ ($p < 0.05$; one-tailed) for the sample of 14 participants, where the estimation of vergence velocity was appropriate. If the remaining two participants (open symbols; R6 and D2) with a questionable subjective vergence velocity were included, the correlation was $r = 0.60$ ($p < 0.05$; two-tailed, $n = 16$). Circles and triangles indicate participants of Riga and Dortmund sub-sample, respectively.

Because of high correlation between two factors – measured fixation disparity and baseline vergence, which could influence the correlation between measured fixation disparity and predictor of fixation disparity, we tested simple measure of convergent-divergent asymmetry in vergence dynamic expressed either as in equation 3.2 (prediction of fixation disparity 2)

$$FD2_{pre} \sim (\sqrt{V_{conv}} - \sqrt{V_{div}})/(\sqrt{V_{conv}} + \sqrt{V_{div}}) \qquad \text{Eq. 3.2}$$

or a simple difference between vergence velocities ($V_{conv} - V_{div}$) (prediction of fixation disparity 3). In equation 3.2, we did not used the corrective factor – baseline vergence.

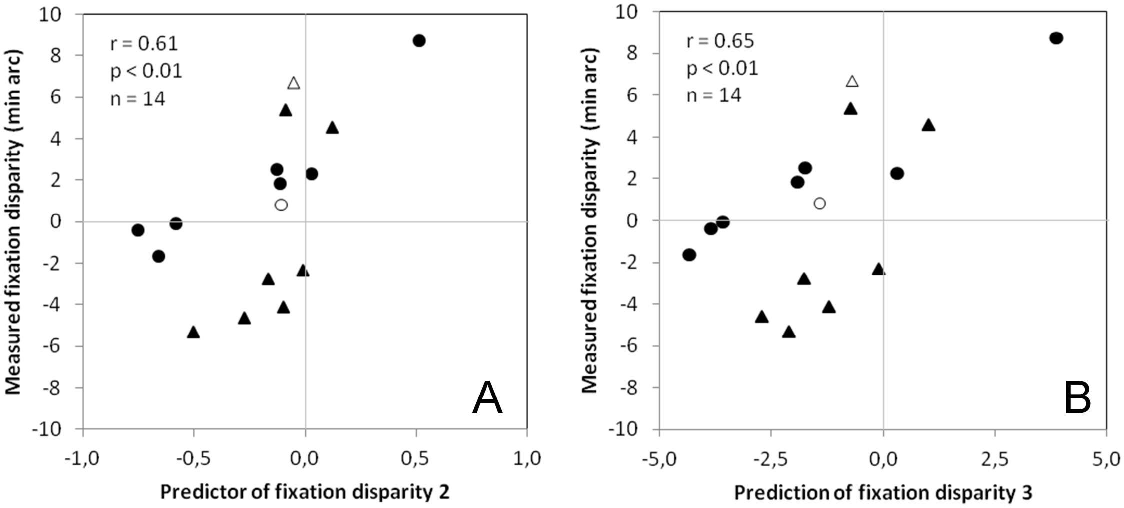

Figure 3.9. Correlation between measured fixation disparity and the predictor of fixation disparity calculated either from Eq. 3.2, where no corrective factor (baseline vergence) was used (A, predictor of fixation disparity 2), and simple difference between convergent and divergent velocities (B, $V_{conv} - V_{div}$, predictor of fixation disparity 3). The correlation was r = 0.61 and r = 0.65 ($p < 0.01$; one-tailed) for the sample of 14 participants, where the estimation of vergence velocity was appropriate. If the remaining two participants (open symbols; R6 and D2) with a questionable subjective vergence velocity were included, the correlation was r = 0.60 and r = 0.63 ($p < 0.01$; one-tailed, n = 16) for A and B situations, respectively. Circles and triangles indicate participants of Riga and Dortmund sub-sample, respectively.

We still had high correlation between measured fixation disparity and predictor of fixation disparity using equation 3.2 (Pearson correlation coefficient r = 0.61, p = 0.02, two-tailed, n = 14 and r = 0.60, p = 0.01, two-tailed, n = 16) and a simple difference between vergence velocities ($V_{conv} - V_{div}$) (Pearson correlation coefficient r = 0.65, p = 0.01, two-tailed, n = 14 and r = 0.63, p = 0.009, two-tailed, n = 16) (see Figure 3.9). Thus, the influence of baseline vergence was weak in most of participants. Only participants with large baseline vergence had significant changes of predictor of fixation disparity.

3.5. Discussion I

As there are different models to explain the performance of the vergence system, it is interesting to look how the vergence dynamic processes are presented in these models. The neural network model of Patel et al.[23] is based on the convergent-divergent asymmetry in dynamic vergence response. It predicts that the static vergence error (fixation disparity) is a result of the disparity vergence mechanism in the convergent and divergent direction. If divergent velocity is larger (smaller) than convergent velocity, an exo (eso) fixation disparity will result. However, control theory based models include only one direction of vergence. At our viewing distance of 60 cm (about 1.7 meter angle, MA[*]) the average participant converges an amount of 0.7 MA relative to the mean resting position of vergence of about 1 MA[37-38]. Thus, from control-type models, fixation disparity is expected to be correlated with convergence velocity, while divergence velocity should be irrelevant. We found that the amount of inter-individual variance (r^2) in fixation disparity explained by convergent velocity alone was 29% (based on coefficient of determination r^2, adj. $r^2 = 0.23$, $r = 0.54$, $p < 0.05$, one-tailed, $n = 13$) compared to 21% (r^2, adj. $r^2 = 0.14$, $r = 0.46$, $p > 0.05$, one-tailed, $n = 13$) explained by divergent velocity. Prediction based on the neural network model (using Eq. 3.1) reached 47% (r^2, adj. $r^2 = 0.42$, $r = 0.68$, $p < 0.05$, one-tailed, $n = 13$). For these calculations, we omitted two participants in Figure 3.5 (R6 and D2), and one additional participant of the Dortmund sub-sample (D4) with a resting vergence much closer than the viewing distance of 60 cm. If we take all participants, prediction based on the neural network model (Eq. 3.1) still explains about 50% (r^2, adj. $r^2 = 0.46$, $r = 0.70$, $p < 0.005$, one-tailed, $n = 16$) of inter-individual variance in fixation disparity. Whereas, convergent velocity alone explains only 35% (r^2, adj. $r^2 = 0.30$, $r = 0.59$, $p<0.05$, one-tailed, $n = 16$) and divergent velocity even less – only 18% (r^2, adj. $r^2 = 0.12$, $r = 0.42$, $p>0.05$, one-tailed, $n = 16$) of inter-individual variance in fixation disparity. This means that the asymmetry was able to explain a larger proportion of variance in fixation disparity than convergence velocity alone, since divergence velocity provided a considerable contribution. Prediction improves by taking into account both the convergent and divergent directions. Similar findings were shortly presented in the previous studies of Jaschinski[25] and Fredenburg & Harwerth[24].

But still such a neural network model could explain at most about 50% (r^2, $n = 16$) of inter-individual difference in fixation disparity. This means that other factors should be involved in physiological processes of fixation disparity origin. Patel et al.[23] had shown the impact of asymmetric vergence velocity on static fixation disparity with an intra-individual paradigm: the individual fixation disparity was modified by varying the pedestal vergence demand (baseline vergence). This intra-individual approach of testing a model has the advantage to keep constant some individual factors that could also affect fixation disparity; such factors introduce additional variance in the present inter-individual approach. Clinically more relevant is an inter-individual approach rather than intra-individual used by Patel et al.[23] The general aim of such an inter-individual approach is to explore the physiological

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[*] Meter angle (MA) – the unit of ocular convergence equal to the amount of convergence required to view binocularly an object at 1 meter and exerting 1 diopter of accommodation (Medical Dictionary).

mechanisms that account for the considerable individual differences that are observed in large, non-selected samples of participants with normal binocular single vision. Additional factors that might play a role include dark vergence, dark focus, accommodation gain, and AC/A-ratio. These four factors were previously analyzed by Jaschinski[30]. He found that these four factors together explained about 20% (r^2) of the variance in fixation disparity at 60 cm viewing distance when natural accommodation was exerted. Thus, it could be interesting to look on other factors in combination with the asymmetry of vergence dynamics to explain the origin of fixation disparity (see Experiment III).

Rashbass and Westheimer[39] observed some difference in vergence dynamics by changing the size of the vergence step stimulus (overshoot and corrective movement for smaller vergence step stimuli and relatively earlier slowed larger movements), but the amplitude of the vergence movements matched the target very well in both directions (the final disparity did not exceed a few min arc). Only one of their participants showed oscillation not only around the final position but also during the movement and it was observed only in one direction (in their subject – during convergence movement) suggesting possible vergence problems not described earlier.

There is also experimental evidence for individual differences in the asymmetry of dynamic vergence responses, provided by Jones[40], Fredenburg and Harwerth[24], Jainta et al.[31], Jaschinski[25]. Analyzing the ratio of the maximum amplitudes of convergence and divergence for thirty participants, Jones[40] observed a skewed distribution of asymmetry: most individuals tended to have slightly larger amplitude of divergence than convergence. An asymmetry was also observed by Fredenburg and Harwerth[24] discussing also its relation to fixation disparity. Among their six participants, two with a large convergent, but missing divergent dynamic response had an eso fixation disparity, while two other participants with a large divergent, but missing convergent dynamic response had an exo fixation disparity. Two participants with symmetric, but week dynamic responses had no fixation disparity.

Different results and opinions considering the symmetry or the asymmetry of vergence step responses could be explained with an aim and a design of the experiments. Sometimes, well trained participants with good vergence responses in both directions are used for experiments if the goal of the research is to analyze and to understand normal vergence movement. By taking casual participants (like in our experiment) to look on a vergence step response as in a usual clinical practice, it is expected to see more variable vergence responses. We observed that there were three types of vergence responses. Besides good vergence response in both convergent and divergent direction, there were participants showing poor convergence or divergence response. Thus, in our sample we noticed that seven of eight participants with an exo fixation disparity showed rather good divergence response (reaching the target divergent state of 60 min arc with a nonius delay of 400 ms or even earlier), but showed virtually no response in convergent direction. Fredenburg and Harwerth[24] and Jainta et al.[31] observed also the fourth type of vergence step responses – symmetrically weakened vergence step response – virtually no response neither in convergent, nor divergent direction. Thus, we could talk about four types of vergence step response patterns: good vergence response in both convergent and divergent direction, virtually no vergence response in both convergent and divergent direction, rather good convergent but no divergent response, and rather good divergent, but no convergent response. It is hard to discuss which pattern will be predominating in the population. It is necessary then to do larger studies including much more participants as in our study.

In principle, the best method for the research laboratory to record objective binocular eye movement are eye trackers, but usually they require – however – elaborated instrumentation, test procedures, and data analyses. The dynamic nonius technique (although needing some time for testing) can be applied much more easily and allows for testing dynamic vergence also in the clinical context. It is known that the vergence response results obtained with nonius technique can deviate from objective recordings with eye trackers, at least in particular conditions of testing[41]. Thus, we considered whether possible limitations of the subjective technique may apply to the present measures of disparity vergence step responses and fixation disparity.

Nonius tests also previously were used to measure dynamic vergence response[24,25,31,42,43]. Nonius measures of disparity vergence step responses could be affected by the following conditions of testing:

1) The visual direction of monocular nonius lines could be modified by those of the adjacent fusion stimuli[44,45], but this effect of capture of visual direction is reduced by flashing the nonius lines as in the present study[46].
2) Only a coarse sampling of the vergence movement is possible with the chosen amounts of nonius delay of 100, 200, 300, and 400 ms for estimating vergence velocity.
3) The vergence eye movement cannot be measured subjectively with arbitrarily short nonius pulses; the shorter the nonius line presentation the more difficult is the judgment of the offset. Therefore, we used duration of 100 ms which is easily perceived by all observers.

4) A certain period of time is required for retinal and central processing until the percept of nonius lines will arise. During this perceptual delay and during the 100 ms nonius flash duration, the vergence movement is going to proceed.

It is difficult to estimate the extent to which these conditions may affect the subjectively measured vergence velocity. Jainta et al.[31] did experiment on 25 healthy participants comparing subjectively and objectively obtained vergence step responses. The stimulus presentation was similar as in our experiment. Nonius lines appeared for 80 ms at fixed nonius delays (0, 100, 200, 300, 400, 1000 ms) after the disparity step stimulus onset. The duration of the disparity stimulus was 2 s and the fixation period (at the baseline vergence stimulus) before the disparity step stimulus varied randomly in the range of 2.75-3 s. The only difference was in the apparatus used for the experiment. They used a mirror stereoscope compared to our experiment where we used shutter glasses to present stimulus dichopticaly. Objective vergence response was measured during the complete subjective test procedure using video-based eye movement tracking system EyeLink II (SR Research Ltd., Canada) to track both eyes simultaneously. Subjective and objective vergence response was obtained for vergence response using 3° (180 min arc) disparity stimulus step at 60 cm distance (baseline vergence of about 6° – slightly depending on the individual inter-pupillary distance).

The main observations of Jainta et al.[31] were that subjective and objective measures were highly correlated (cross-correlation) in any case – even in participants with poor either convergence, divergence or both responses (r = 0.9). Lowest cross-correlation was observed for those participants (2/16) who had a very poor vergence performance (both with subjective and objective methods). Thus, inter-individual differences can be identified with the nonius method. Analyzing group results, only half of the amplitude of the disparity step stimulus of 3° (both in convergence and divergence direction) was reached in the objective measurements (1000 ms after the step stimulus onset). They explained it by the fact, that some participants hardly ever moved their eyes during all presentations showing poorer response either in convergence, divergence or both directions as described also earlier[24,25,40], as observed also in our experiment. Comparing final level of subjective and objective vergence response, Jainta et al.[31]concluded that subjective method underestimated vergence velocity and overestimated final vergence state.

Thereby, their results showed:

- The maximal vergence velocity was well correlated between both methods, despite subjective method showed a clear underestimation for both vergence directions. This underestimation could be due to limitations of subjective method and technique used to find maximal vergence velocity (maximal slope from three pairs of nonius delays: 100-200, 200-300, 300-400 ms). Thus, the sampling interval of 100 ms is too large to detect the moment of maximal velocity.

- The vergence amplitude reached at the final phase of response also was well correlated between both methods; just subjective method overestimated the objectively measured vergence response by about 25 min arc in most conditions, except for the 1000 ms nonius delay in the convergent direction. In most of their participants, the vergence response was nearly saturated after 400 ms. So 400 ms can also be used in subjective method to estimate final amplitude of vergence movement.[31]

Thus, Jainta et al.[31] suggested that "the dynamic nonius test allows to identify whether a subject has a relatively high or low disparity vergence performance; this could be sufficient for the assessment of vergence dynamic in the clinical context where objective binocular eye movement recordings are not applicable. … the present dynamic nonius test may be a diagnostic alternative: the computer-controlled procedure is independent of motivation effects and has a high test-retest reliability in adults and in children"[47].

Also Rashbass and Westheimer[39] looked on the duration of vergence movement. For 2° step stimulus, latency was about 160 ms; soon after vergence response developed constant velocity and maintained it for nearly 200 ms, after which the velocity diminished. Almost full amplitude of stimulated vergence was reached in about 800 ms, so that in total about 1 sec was necessary between the onset of the stimulus and the stabilization of the response at the new level of eye vergence.

We analysed what amplitude was reached at the final phase of vergence response (at 400 and 1000 ms of nonius delays). We observed that about 50% for convergent and about 84% for divergent stimulus amplitude was reached at 1000 ms of nonius delay. The quite large standard deviation can be explained with the large inter-individual variability of vergence step response pattern, having large group of participants showing poor convergence, divergence. If we analyse only those participants showing good vergence step response either in convergent or divergent direction, the amplitude reached is higher – about 95% and 98% for convergent and divergent response, respectively. The minimal amplitude reached was 87% for both convergent and divergent step responses. The result of group analyses is shown in Table 3.3.

Following the finding of Jainta et al.[31] we analyzed also amplitude reached at 400 ms nonius delay (see Table 3.3). Jainta et al.[31] observed that the vergence response was nearly saturated after 400 ms and reached more than 60% of vergence step response amplitude for group of participants. In our experiment, participants showing good convergence response reached about 75% and 95% of convergence and divergence response, respectively, with the minimal amplitude reached 69% and 81% for convergence and divergence responses, respectively. Thus, participants having good vergence step response reached more than 60% of vergence step response at even 400 ms nonius delay.

Table 3.3

The results of group analyses for vergence response amplitude reached at 400 ms and 1000 ms nonius delays.

	Convergent step response				Divergent step response			
Nonius delay (ms)	Group average (%)	SD for group (%)	Average for selected group* (%)	SD for selected group* (%)	Group average (%)	SD for group (%)	Average for selected group** (%)	SD for selected group** (%)
400	41	46	75	5	72	43	95	11
1000	50	48	95	7	84	31	98	9

* Selected group – participants showing good convergence step response (R1, R8, D3).

** Selected group – participants showing good divergence step response (R1, R3, R4, R5, R7, R8, D3, D5, D8).

Analyzing the vergence response graphs (see Figure 3.4), the vergence response saturation is reached at 400 ms and only stabilizes at the later time phases. Thus, nonius delay of 400 ms could be enough to analyze subjectively vergence step responses and to identify whether a person has a relatively high or low disparity vergence performance.

Futher, our subjective vergence velocity reached maximal values of about 5°/s, with the 1° disparity step stimulus in the present study. It is known that vergence velocity increases about linearly with the amount of the stimulus[32]. Accordingly, Patel et al.[23] found maximal objective values of vergence velocity up to 12°/s with the 2° disparity step stimulus (at a 6° pedestal vergence demand as in the present study). It is plausible that the nonius technique will under-estimate high vergence velocity, which is confirmed by the following data available from study of Jainta et al.[31] with 3° disparity step stimuli. Nonius technique and objective recordings gave similar mean values of vergence velocity (4.9 vs 5.1°/, divergent direction), while two experiments with convergent stimuli gave mean objective amounts of velocity of 9.1 and 9.7°/s and corresponding subjective estimations of only 6.7 and 5.2°/s (but still a high correlation of 0.9). Thus, subjective estimations of vergence velocity appear to be valid when the amount of vergence velocity is up to about 5°/s (as in the present conditions of testing).

Our subjective measure of fixation disparity appears to be useful since the present results are physiologically plausible in relation to vergence dynamics and in agreement with a current model of vergence[23].

3.6. Conclusions I

1. Our measurements replicate previous observations, that the nonius method provides stable measures of individual vergence performance (fixation disaprity, vergence step response and baseline vergence). The test-retest correlation resulted in r = 0.90 for fixation disparity, r = 0.94 for the vergence step response (median across all conditions tested), and r = 0.86 for baseline vergence (median across all conditions tested).
2. Our results demonstrate, that the individual differences in the asymmetry of vergence dynamics in convergent and divergent direction were able to explain at most 50% (r^2) of the inter-individual variance in fixation disparity in the present group of participants (which included more large eso and exo cases than random sample) as proposed by Patel et al.[23] in the neural network model. To improve this prediction, additional factors like dark vergence, dark focus, accommodation gain, and AC/A-ration could be added to the analyses.
3. Our results demonstrate weak influence of baseline vergence on the correlation between measured fixation disparity and the predictor of fixation disparity. Only participants with large baseline vergnence have significant influence on the predictor of fixation disparity. For all that, we suggest, that the effect of baseline vergence should be analyzed before prediction of fixation disparity is made using the neural network model.
4. Our results show that 400 ms nonius delay is enough to evaluate the quality of vergence step response for subjective measurements. 60% is a minimum of vergence step response amplitude to be reached at a nonius delay of 400 ms for a good vergence step response when the vergence step stimulus size is 1°. Following this criteria, inter-individual differences in the asymmetry of vergence step response could be observed in large, non-selected groups of participants with normal binocular single vision. We

found four categories:

- good convergent and divergent response,
- good convergent response and poor divergent response,
- good divergent response and poor convergent response,
- poor convergent and divergent response.

4. Dynamic and static parameters of vergence response with changing viewing distance and disparity vergence step stimulus size (Experiment II)

4.1. Purpose of the Experiment II

It is well known that viewing distance affects fixation disparity[26,27,29] and that the disparity vergence step size affects the vergence dynamics[2,24,39,40,48]. Therefore, the purpose of Experiment II was to evaluate the reliability of the nonius method for subjectively measuring vergence responses in two conditions of vergence load: (1) changing viewing distance (30 cm, 40 cm, 60 cm, and 100 cm) and with constant step stimulus size (60 min arc), and (2) changing vergence step stimulus size (15 min arc, 30 min arc, 60 min arc, 120 min arc) at constant viewing distance (60 cm). Thus, we explored the subjective method with dichoptic nonius lines to provide physiologically plausible estimation of individual differences in dynamic asymmetry of vergence. Additionally, we investigated the effect of distance and disparity step stimulus size on the relation between fixation disparity and individual differences in the asymmetry of vergence dynamics observed in Experiment I. These results were compared with proximity fixation disparity line showing changes of the fixation disparity at different viewing distances (30 cm, 40 cm, 60 cm, and 100 cm).

4.2. Participants II

We tested 7 participants (age 21-32 years, mean age - 23 years; visual acuity 1.0 or better (in decimal units) with correction (if needed, three participants wore refractive corrections during testing) at the test viewing distance; with good convergence (6-10 cm), binocular single vision and stereopsis). All participants were participated only in the Experiment II. The experiment were undertaken with the understanding and written consent of all 7 participants and followed the tenets of the Declaration of Helsinki.

4.3. Experimental design II

All participants had two repeated sessions on separate days, in order to evaluate the test-retest reliability. Each session comprised three parts of measurements:

1) fixation disparity measurement at 30, 40, 60, and 100 cm viewing distances;
2) dynamic vergence response measurement with step disparity stimuli of 60 min arc with four nonius delays (100, 200, 300, and 400 ms) at 30, 40, 60, and 100 cm viewing distances including both convergent and divergent directions

inducing an accommodative stimulus of 3.33, 2.50, 1.67, and 1.00 D, respectively. We started from 30 cm distance and proceeded with longer distances up to 100 cm viewing distance.

3) dynamic vergence response measurement for step disparity stimuli of 15, 30, 60, and 120 min arc with four nonius delays (100, 200, 300, and 400 ms) at 60 cm viewing distance both convergent and divergent directions. We started with 15 min arc vergence step stimulus size and preceded with larger vergence step stimulus sizes up to 120 min arc. We tried also 240 min arc vergence step stimulus size.

The whole experiment was run in a separate room with dim lighting. The order of all four runs (with different nonius delays) for all vergence response measurements was randomly varied. After two or three runs participants had a rest of about 5 min and after every 10 runs participants had a rest of 20 min. Thus each session took about 4.5-5 hours, including rests. Periods of near vision did not occur, thus did not induce vergence adaptation. For data analyses, we used statistics available on R software, Microsoft Excel, Origin, and MedCalc.

4.4. Results II

4.4.1. Disparity vergence step response at 60 min arc and 60 cm viewing distance

We observed mainly two types of vergence step responses (as described in Experiment I), if we looked on the data obtained at 60 cm distance and with 60 min arc disparity step stimulus size (see Figure 4.1) (main parameters used to describe types of vergence step respones in the Experiment I). Most of the participants (five from seven; S2, S3, S4, S6, S7) showed an ordinary response reaching final level near the stimulus amplitude of 60 min arc for boths vergence step stimulus – convergent and divergent at about 400 ms nonius delay. One participant (S5) showed a little bit weaker response pattern in both directions reaching only a half (about 30 min arc) of final level for boths vergence step stimulus – convergent and divergent at about 400 ms nonius delay. And one participant (S1) showed virtually no convergent response and weak divergence response reaching only half of stimulus step size.

Vergence step response amplitude reached at 400 ms nonius delay is shown in Table 4.1. If we take 60% as a limit for both convergence and divergence step response at 400 ms nonius delay (as we suggested in Experiment I), there were 5 participants reaching this criteria in both convergence and divergence directions. Only two participants (S1 and S5) could not reach this criteria (see Figure 4.1).

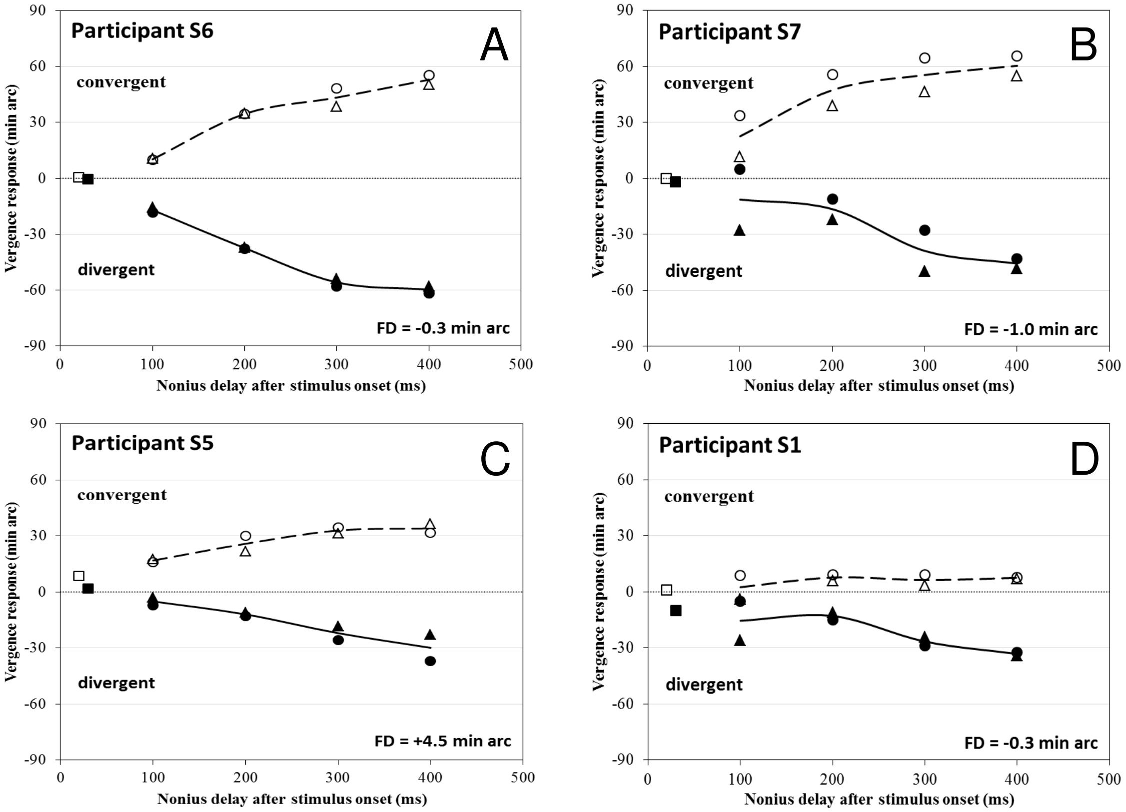

Figure 4.1. Examples of disparity vergence step responses in four participants. A and B. Two participants (S6 and S7) showed ordinary disparity vergence step responses and reaching final level near the stimulus amplitude of 60 min arc at about 400 ms nonius delay. C. One participant (S5) showed weaker response pattern in both directions reaching only the half of the stimulus amplitude (about 30 min arc) at about 400 ms nonius delay. D. One participant (S1) showed virtually no convergent response and weak divergent response. Positive and negative response values refer to convergent and divergent states (corresponding to the viewing distance of 60 cm). Responses for convergent and divergent step stimuli (opne and closed symbols, respectively) are plotted as a function of the amount of nonius delay (100, 200, 300, and 400 ms) after the disparity step stimulus onset. The pairs of data points (triangles and circles) refer to the first and second session to illustrate the reliability; the lines show the mean values. The two data points near 0 ms indicate the vergence state reached 1000 ms after the disparity stimulus was switched off and replaced by the baseline fusion stimulus; these measurements of baseline vergence states are shown separately for convergent and divergent trials (open and closed squares), but averaged across the four amounts of nonius offset and across test and retest data. In the right lower corner the magnitude of fixation disparity (FD; mean of two sessions) is given.

Table 4.1

Vergence step response amplitude reached at 400 ms nonius delay for each participant expressed in percentage.

	Convergent step response						Divergent step response					
Participant	Amplitude Day1 (min arc)	Amplitude Day1 (%)	Amplitude Day2 (min arc)	Amplitude Day2 (%)	Amplitude average (min arc)	Amplitude average (%)	Amplitude Day1 (min arc)	Amplitude Day1 (%)	Amplitude Day2 (min arc)	Amplitude Day2 (%)	Amplitude average (min arc)	Amplitude average (%)
S1	7	12	8	13	8	13	-34	57	-33	54	-33	55
S2	46	76	29	49	37	62	-56	93	-54	91	-55	92
S3	48	80	47	78	47	79	-61	102	-58	97	-60	100
S4	51	85	62	103	56	94	-50	83	-52	87	-51	85
S5	37	61	32	53	34	57	-23	38	-37	62	-30	50
S6	50	84	55	92	53	88	-58	96	-62	103	-60	100
S7	55	92	66	110	60	101	-48	81	-43	72	-46	76
Av	42	70	43	71	42	71	-47	79	-48	81	-48	80
SD	16	27	21	35	18	30	14	23	11	18	12	20

Av – average; SD – standard deviation

4.4.2. Disparity vergence step response changing disparity step simulus size

We compared the results of disparity vergence step responses changing the size of vergence step stimuli (15, 30, 60, and 120 min arc) to see if the response pattern will be changed. The difference between two sessions were much smaller compared to the inter-individual variability of the data at each nonius delay (as shown by Bland-Altman analyse). At the different nonius delays, the variability of the data and also the difference between two sessions was similar as ANOVA analyse showed no effect ($p > 0.05$). Only the size of the disparity vergence step response and individual factors had statistically significant effect on the vergence response. Thus, it allowed us to put together the results from different nonius delays for each disparity stimulus step size.

Data showed high test-retest correlations (see Table 4.2) at any size of vergence step response. Using Bland-Altman analyzes, there was significant increase of standard deviation of difference between two sessions for larger vergence step stimuli especially for 120 min arc step stimuli. Similarly, the standard deviation (SD) of the difference and the coefficient of repeatability increases about proportionally with the step size.

We tried also 240 min arc or 4° large vergence step stimulus. But most of participants complained they were not able to fuse the stimulus. They saw double through all the experiment and thus the results of the psychophysical test were not applicable. We excluded those results from final analyzes.

Table 4.2

Test-retest correlation, slope of test-retest regression line, standard deviation of the difference between the two repeated measurements, and coefficient of repeatability for vergence step response changing size of vergense step stimuli.

	Convergent step response				Divergent step response			
Disparity step stimuli size (min arc)	Test-retest correlation (r)	Slope of regression line ± standard error	SD of the difference (min arc)	Coefficient of repeatability	Test-retest correlation (r)	Slope of regression line	SD of the difference (min arc)	Coefficient of repeatability
15	0.80	0.84 ± 0.12	2.1	4.2	0.88	0.85 ± 0.09	2.4	4.7
30	0.78	0.94 ± 0.15	4.8	9.4	0.81	0.88 ± 0.13	6.1	12.0
60	0.83	0.95 ± 0.12	10.3	20.1	0.84	0.93 ± 0.12	10.3	20.3
120	0.82	0.99 ± 0.14	22.4	43.8	0.83	0.89 ± 0.12	20.9	41.1

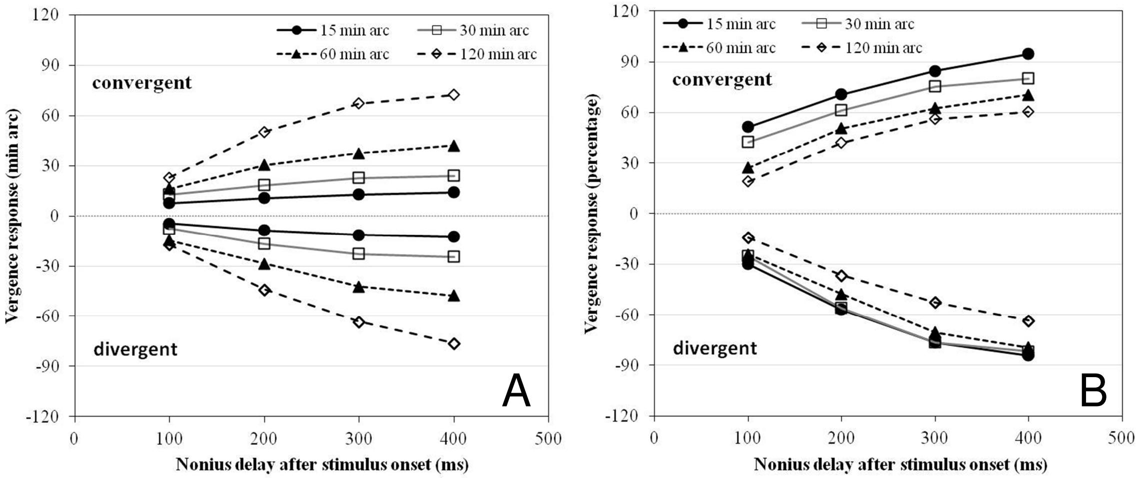

Figure 4.2. Group mean results of disparity vergence step responses expressed in min arc (A) and in percentage (B), if the disparity vergence step stimulus size was changed (15, 30, 60, and 120 min arc) at 60 cm viewing distance. Vergence step response became much weaker with increasing step stimulus size. Positive and negative response values refer to convergent and divergent states. Responses for convergent and divergent step stimuli (open and closed symbols, respectively) are plotted as a function of the amount of nonius delay (100, 200, 300, and 400 ms) after the disparity step stimulus onset.

Analysing mean values of all participants, we observed the expected increase of the response (minor) with the size of the step stimulus (see Figure 4.2A). As there were used different stimulus sizes, we compared the vergence step response amplitudes (expressed in percentage) reached at different nonius delays. As we described previously, 60% is a minimum of vergence step response amplitude to be reached at a nonius delay of 400 ms for a good vergence step response when the vergence step stimulus size is 60 min arc or 1°. Jainta et al.[31] described similar criteria using larger vergence step stimulus (180 min arc = 3°). Thus, we looked what step response size (in percentage) was reached at 400 ms nonius delay for a group mean at each vergence step stimulus sizes.

Size of vergence step response was in a range of 95% – 60% and 84% – 64% for convergence and divergence response, respectively, at 400 ms nonius daley for disparity vergence step response from 15 min arc up to 120 min arc. As vergence step stimulus size increased, the relative amplitude of vergence step response (% of step size) decreased in a group mean (ANOVA: $p << 0.001$) (see Figure 4.2B).

As the group of participants is small ($n = 7$) and the previous results showed the large inter-individual difference in disparity vergence step response, the effect observed for a group mean results could be misleading for individual subjects. Thus, we analyzed individual performance of each participant and observed that vergence step response pattern was kept the same by changing vergence step stimulus size (see Figure 4.3) even if participant showed good or bad vergence response.

It looks harder to keep good vergence responses (analysing relative amplitude, % of step stimulus) with larger vergence step stimulus sizes. We tested this assumtion using ANOVA test for two-factors with replications (see Table 4.3). Changes of vergence step response at different nonius delays were observed for each participant for both convergent and divergent step responses. Only one participant S1 had no convergence response independently of the size of vergence step response (see Figure 4.3D). It confirms our previous observations. This participant showed no vergence step response neither at different viewing distances, nor with different sizes of vergence step stimuli. One participant (S7) showed 100% responses at any size of convergence step response: he had good convergence response independent of the size of step stimuli (see Figure 4.3B). As analyzed later, participant S7 showed also good convergence response independently of the viewing distance. Thus, participants having no vergence problems will keep very good vergence response (participant S7 reached 90-104% of stimuli size already at 400 ms nonius delay) independently of the size of vergence step response and viewing distance.

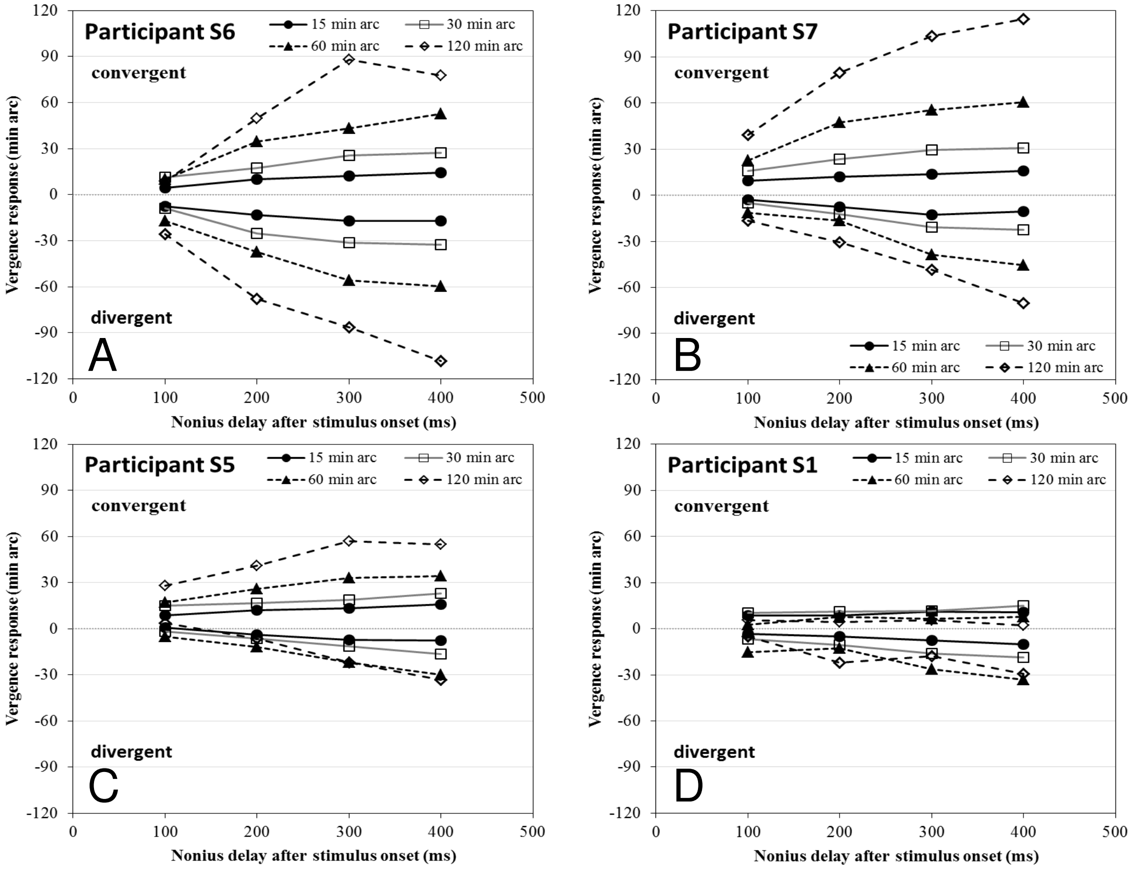

Figure 4.3. Examples of disparity vergence step responses in four participants, if the disparity vergence step stimulus size was changed (15, 30, 60, and 120 min arc) at 60 cm viewing distance. A and B. Two participants (S6 and S7) with ordinary disparity vergence step responses for both, convergent and divergent step stimuli. Participant S6 (A) showed weaker convergence response for 120 min arc disparity stimulus step size only. Participant S7 (B) showed weaker divergence step response for all stimulus step sizes at 400 ms nonius delays. Similar response was observed also in participants S2, S3, S4 either showing weaker convergent (S2 and S3) or divergence (S4) step responses. C. One participant (S5) with weaker response pattern in both directions. Vergence step response became much weaker with increasing step stimulus size (like 120 min arc). D. One participant (S1) with virtually no convergent response and weak divergent response. Vergence step response became much weaker with increasing step stimulus size. Positive and negative response values refer to convergent and divergent states. Responses for convergent and divergent step stimuli (open and closed symbols, respectively) are plotted as a function of the amount of nonius delay (100, 200, 300, and 400 ms) after the disparity step stimulus onset.

The rest of participants showed statistically significant influence of the size of convergence step stimuli (see Table 4.3). Increasing the size of step stimuli, relative convergence response (% of step size) deteriorated. At the beginning we thought this deterioration is mainly due to the 120 min arc stimuli. But the analyzes (ANOVA) showed, this deterioration appeared also for smaller stimuli: for the six participants (S1-S6), convergence step response deteriorated gradually with increasing size of the stimuli. Thus, it is harder for a person to keep proper (i.e. near 100%) convergence response for larger vergence step stimuli.

Table 4.3

The results of ANOVA test for two-factors with replications for each participant analysing effect of the nonius delays and vergence step stimulus size comparing the vergence step response amplitudes expressed in percentals reached at different nonius delays. A significant effect of nonius delay means an increase in relative response with longer nonius delays. A significant effect of step stimulus size means that the relative amplitude of the response (% of step size) decreases with step size.

	Convergent step response				Divergent step response			
Participant	Effect of nonius delays (p)	Effect of the vergence step stimulus size (p)	Effect of the vergence step stimulus size without 120 min arc (p)	Interaction (p)	Effect of the vergence step stimulus size (p)	Effect of the vergence step stimulus size (p)	Effect of the vergence step stimulus size without 120 min arc (p)	Interaction (p)
S1	ns	<0.0001	<0.0001	ns	<0.0001	<0.0001	ns	ns
S2	0.0004	0.001	0.014	ns	<0.0001	<0.0001	0.015	ns
S3	<0.0001	0.0001	0.019	ns	<0.0001	0.0015	ns	ns
S4	0.0004	0.016	0.014	ns	<0.0001	ns	ns	ns
S5	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001	ns	ns
S6	<0.0001	0.0005	ns	ns	<0.0001	<0.0001	0.0009	ns
S7	0.0001	ns	ns	ns	0.001	ns	ns	ns

ns – not significant

A little bit different effect was observed for divergence step response. For all, a divergence response increase was observed with larger nonius delays. Only two participants (S4 and S7) showed no influence of the size of the vergence step stimuli on the relative response. Looking on the results excluding 120 min arc stimuli, most of the participants showed no statistically significant effect of stimuli size. Thus, most of the effect was produced by the larger step stimuli (120 min arc). Therefore, we can conclude divergence response will worsen for larger step stimulus sizes (120 min arc (2°) and larger). Smaller step stimulus sizes (1° and less) have weak influence on the relative divergence step response pattern.

We observed inter-individual differences in vergence step response on different vergence step stimuli. Using LC shutter glasses and nonius technique to evaluate vergence step response, it is more difficalt to keep proper (100%) vergence response with larger step stimulus sizes. As none of our participants had clinically detectable vergence problems and asthenopia, the clinically reliable vergence response can be observed using 60 min arc (1º) vergence step stimulus size at 60 cm viewing distance. This will not produce artificial vergence problems examining naïve (not trained) participants.

4.4.3. Disparity vergence step response changing viewing distance

We compared the results of disparity vergence step responses changing the viewing distance (30, 40, 60, and 100 cm) to see if the response pattern will be changed. The difference between two sessions were much smaller compared to the variability of the data at each nonius delay (as shown by Bland-Altman analyze). There were no influence of nonius delay neither on the variability of the data at each nonius delay, nor the difference between two sessions (ANOVA: $p > 0.05$) for divergence movement. For convergence response, there was no influence of nonius delay on the difference between two sessions, but the variability of the data increased (ANOVA: $p < 0.05$) with increasing vergence response. This effect was stronger for larger nonius delays. Still the variability of data at each nonius delay was in a wide range because of individual variance of vergence step response pattern among participants.

Table 4.4

Test-retest correlation, slope of test-retest regression line, standard deviation of the difference between the two repeated measurements, and coefficient of repeatability for vergence step response at different viewing distances.

	Convergent step response				Divergent step response			
Viewing distance (cm)	Test-retest correlation (r)	Slope of regression line ± standard error	SD of the difference (min arc)	Coefficient of repeatability	Test-retest correlation (r)	Slope of regression line	SD of the difference (min arc)	Coefficient of repeatability
30	0.89	0.78 ± 0.08	8.6	16.9	0.94	1.07 ± 0.07	5.6	11.0
40	0.63	0.75 ± 0.18	15.9	31.1	0.88	0.98 ± 0.11	9.5	18.6
60	0.83	0.95 ± 0.12	10.3	20.1	0.84	0.93 ± 0.12	10.3	20.3
100	0.92	0.97 ± 0.08	7.2	14.1	0.92	0.94 ± 0.08	8.3	16.2

To see the overall effect of viewing distance on vergence step response, we put together the results from different nonius delays for each viewing distance (see Table 4.4). They showed no tendency for standard deviation of difference between two sessions relative to the viewing distance. From all this analyses, we concluded that data showed high test-retest correlations (see Table 4.4) and, thus, good reliability at any viewing distance.

Analysing mean values of all participants, the vergence step responses kept the same pattern (see Figure 4.4) at all viewing distances. As viewing distance increased, the amplitude of vergence step response reached at 400 ms nonius delay decreased (ANOVA: $p << 0.001$) but still showed good relative vergence response (79% – 62% and 88% – 74% for convergent and divergent response, respectively, for 30 up to 100 cm viewing distance).

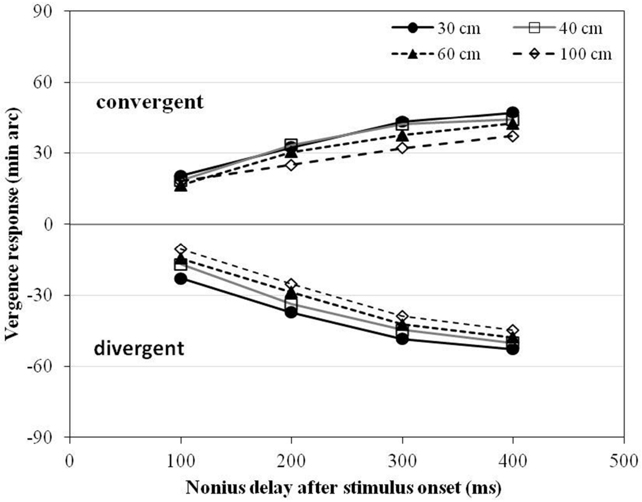

Figure 4.4. Group mean results of disparity vergence step responses on 60 min arc vergence step stimulus if the viewing distance was changed (30, 40, 60, and 100 cm). Vergence step response became weaker with increasing viewing distence. Positive and negative response values refer to convergent and divergent states. Responses for convergent and divergent step stimuli (open and closed symbols, respectively) are plotted as a function of the amount of nonius delay (100, 200, 300, and 400 ms) after the disparity step stimulus onset.

Similar as analysing effect of disparity vergence step stimuli size on vergence response, the effect observed for a group mean results changing viewing distance could be misleading for individual subjects. We analyzed individual performance of each participant and observed that vergence step response pattern was kept the similar as the mean (see Figure 4.5) at all viewing distances. Only some participants showed weaker vergence step response (either for convergence or divergence) when viewing distance was changed to 100 cm (see Figure 4.5).

It seems to be more difficult to keep proper vergence responses at larger distances.

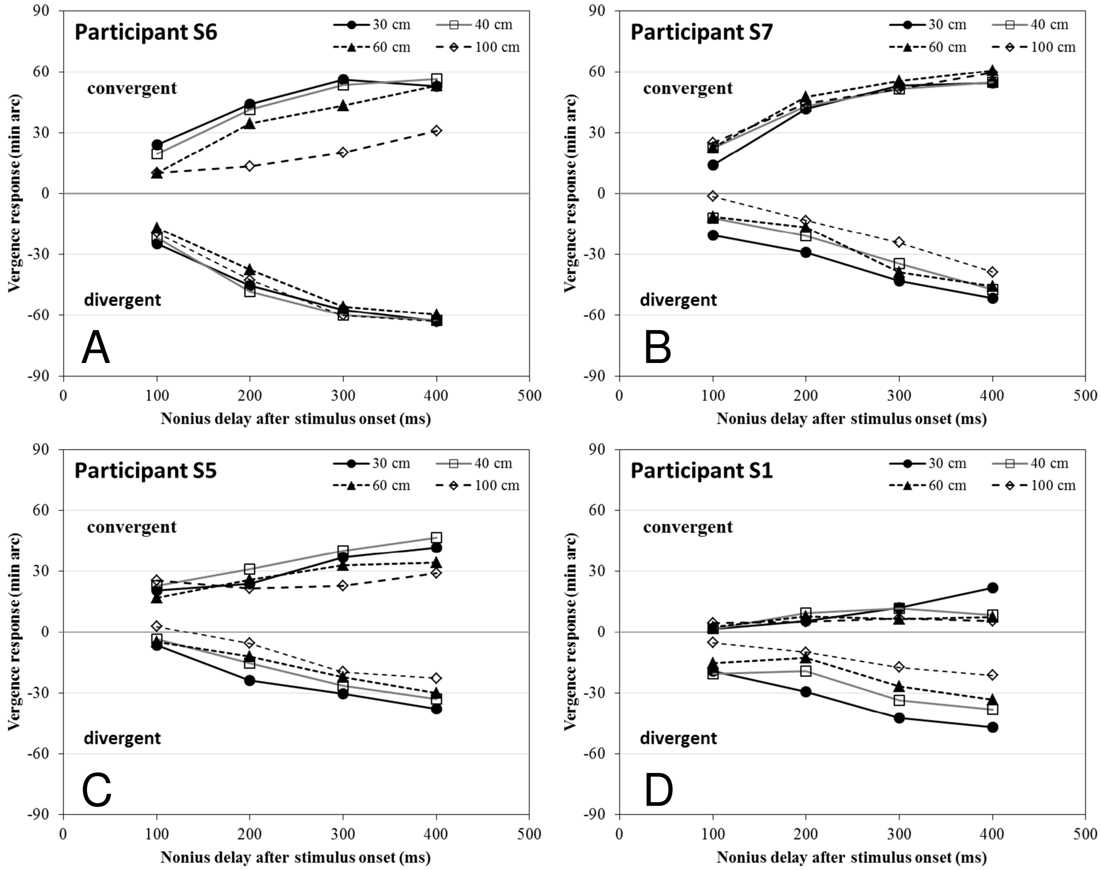

Figure 4.5. Examples of disparity vergence step responses in four participants, if the viewing distance was changed (30, 40, 60, and 100 cm) for 60 min arc step stimulus size. All participants showed similar response pattern irrespective to viewing distance. Only some participants showed weaker disparity vergence step response (either for convergent – like participant S6, or divergent – like participant S7) at 100 cm viewing distance. A and B. Two participants (S6 and S7) with ordinary disparity vergence step responses for both, convergent and divergent step stimuli. Similar response was observed also in participants S2, S3, S4. C. One participant (S5) with weaker response pattern in both directions. D. One participant (S1) with virtually no convergent response and weak divergent response. Positive and negative response values refer to convergent and divergent states (corresponding to the viewing distance). Responses for convergent and divergent step stimuli (open and closed symbols, respectively) are plotted as a function of the amount of nonius delay (100, 200, 300, and 400 ms) after the disparity step stimulus onset.

We tested this assumtion using ANOVA test for two-factors with replications (see Table 4.5). All participants except one (S1) increased their convergence step response with increasing nonius delay. Participant S1 had no convergence response (independently of the viewing distance). Only three participants (S2, S5, S6) showed statistically significant influence of the viewing distance on the convergence step response; it worsened with increasing viewing distance. The worst vergence step response was observed at 100 cm viewing distance. All participants had stronger or weaker divergence step response, but only two participants (S4, S7) had no influence of viewing distance on their vergence step response. Five participants (S1, S2, S3, S5, S6) had weaker divergence response with increasing viewing distance. Interactions of those two factors – nonius delays and viewing distance – in most of the cases was not statistically significant ($p > 0.05$).

Table 4.5

The results of ANOVA test for two-factors with replications for each participant analyzing effect of the nonius delays and viewing distance. A significant effect of nonius delay means an increase in vergence step response with longer nonius delays. A significant effect of viewing distance means that the amplitude of the vergence step response decreases with increasing viewing distance.

	Convergent step response			Divergent step response		
Participant	Effect of nonius delays (p)	Effect of the viewing distance (p)	Interaction (p)	Effect of nonius delays (p)	Effect of the viewing distance (p)	Interaction (p)
S1	ns	ns	ns	<0.0001	<0.0001	ns
S2	0.008	0.03	ns	<0.0001	<0.0001	0.003
S3	<0.0001	ns	ns	<0.0001	<0.001	0.02
S4	0.001	ns	ns	<0.0001	ns	ns
S5	<0.0001	0.002	ns	<0.0001	0.002	ns
S6	<0.0001	<0.0001	0.01	<0.0001	0.005	ns
S7	<0.0001	ns	ns	0.0003	ns	ns

ns – not significant

We conclude that the vergence load with changing viewing distance produces inter-individual differences in vergence step response performance depending on the direction of the stimulus (either convergent or divergent). If it is difficult to keep proper vergence step response (either convergence or divergence) at one of the nearest distances, the increase of viewing distance will produce even worser vergence step response.

4.4.4. Predictor of fixation disparity with varying the viewing distance and vergence step stimulus size

Similary as we analysed in Experiment I, we used the neural network model of the disparity vergence system proposed by Patel et al.[23]. We wanted to see if the predictor of fixation disparity has the same correlation with measured fixation disparity when viewing distance and disparity step stimulus size are changed. Maximal vergence velocity was estimated by finding the maximum of three linear changes in vergence state for three differences of nonius delays (100-200; 200-300; 300-400 ms).

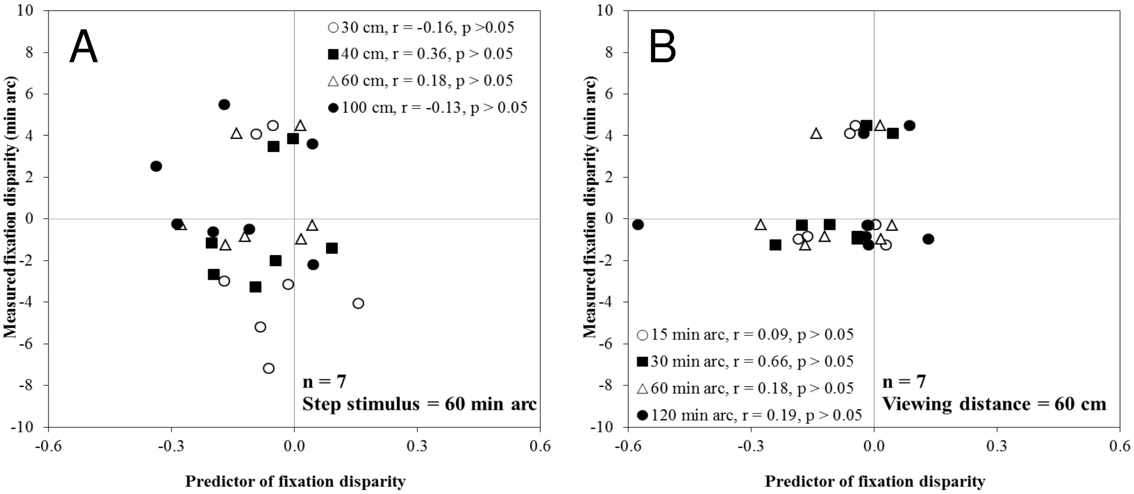

Figure 4.6. Correlation between measured static fixation disparity and predictor of fixation disparity. A. For 60 min arc disparity step stimulus at various viewing distances (30, 40, 60, 100 cm). B. For various disparity step stimuli (15, 30, 60, 120 min arc) at 60 cm viewing distance.

As we can see from Figure 4.6, the correlation is weak for both different viewing distances and different disparity step stimuli sizes (even for data obtained at 60 cm and using 60 min arc step stimulus size as used in Experiment I). The possible explanation for such a small correlation could be a small number of participants (n = 7), small variability of vergence step responses, and narrow variety of values for predictor of fixation disparity (only in a range -0.34 to 0.16). In addition, inter-individual variations of vergence step response were observed for the effect of vergence load induced either by the step stimulus size or viewing distance. These variations can affect the asymmetry of vergence step response and accordingly predictor of fixation.

4.4.5. Proximity fixation disparity line

Jaschinski[30] showed changes of measured fixation disparity at different viewing distances. Fixation disparity moved to a more exo position with decreasing viewing distance. To see if our results follow this observation, we measured fixation disparity at four different distances (30, 40, 60, 100 cm) and ploted them as a function of the viewing distance expressed in meter angles[*] (see Figure 4.7). Also our experiment showed the same changes of measured values of fixation disparity. With small number of participants (n = 7), we just describe the expected trends based on mean values by the following regression analyses. Despite the high variance of fixation disparity data between participants, there was a clear linear effect of distance on the measured fixation disparity (r = 0.98, p = 0.024).

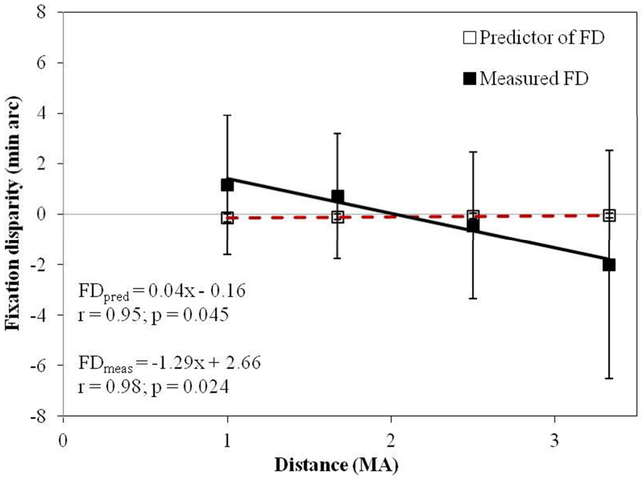

Figure 4.7. Proximity fixation disparity line for measured fixation disparity (filled squares) and predictor of fixation disparity (open squares) (group mean ± standard deviation).

Additionally we plotted calculated predictor of fixation disparity as a function of the viewing distance (see Figure 4.7). Whereas, despite the linear relation between distance and predictor of fixation disparity (r = 0.95, p = 0.045), the change of predictor of fixation disparity relatively to the viewing distance was very small (see Figure 4.7). The slope of the regression line is not different from zero (t-test: p > 0.05, one-tailed).

Thus, it seems vergence asymmetry expressed as predictor of fixation disparity can not fully explain the changes observed for fixation disparity at different viewing distances.

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[*] Meter angle (MA) – the unit of ocular convergence equal to the amount of convergence required to view binocularly an object at 1 meter and exerting 1 diopter of accommodation (Medical Dictionary).

4.5. Discussion II

In the Experiment II, we looked on the effect of two disparity factors – disparity step stimulus size (15 min arc, 30 min arc, 60 min arc, and 120 min arc) and the viewing distance (30 cm, 40 cm, 60 cm, and 100 cm) on the performance of vergence movement and on the predictor of fixation disaprity.

Similarly as in Experiment I, we could observe different types of vergence step responses – either good convergence and divergence, or weak one of the vergence responses (either convergence or divergence). There were observed inter-individual variance in vergence response by changing either viewing distance or disparity vergence step stimulus size and it depends on the direction of the stimulus (either convergent or divergent). But still participants kept the same vergence response pattern as observed at 60 cm and with 60 min arc step stimulus (as used in Experiment I). Additionally, if the person had weak vergence step response (either convergence or divergence), it was bad at any viewing distance and with any of stimulus step size. Similary, if the person had really good vergence performance (either convergence or divergence), it was kept good even if those two factors was changed.

It was interestingly that our participants were not able to perform 240 min arc or 4º large vergence step stimulus. They complained they were not able to fuse the stimulus, saw double through all the experiment. For example, Erkelens et al.[48] used large disparity steps up to 10º (600 min arc) for 5 participants. They used red-green filters to dissociate both eyes and magnetic scleral search coils method to register vergence response at 1.43 m viewing distance. They observed that responses to disparities up to 2º (120 min arc) are sustained – the response saturated at the limit of convergence. But larger disparities (4º and more) showed transient characteristics – after large converging movement the angle of convergence gradually declined to about its initial value. For disparities larger than 5º amplitudes of the transient responses decreased and occasionally responses were completely absent. They suggested: "transient character of responses was apparently due to adaptation of the vergence system". This also agrees with our observation and partly explained why our participants were not able to perform 4º vergence step response. It showed that for our method (nonius test with LC shutter glasses) it is inconvenient to use large step stimulus sizes (like 4º). Even vergence step response on 2º step stimulus was hard to perform. Majority of our participants showed no influence of step stimulus size on relative vergence response (% of step stimulus) (especially divergence response) if we excluded 2º step stimulus from analyses. Thus, it is much better to perform 60 min arc or 1º step stimulus for vergence if LC shutter glasses are used during nonius test.

We observed decrease in the relative amplitude of response at 400 ms nonius delay for both convergence and divergence, if disparity vergence step stimulus size was increased. It corresponds to the observation described by Ogle et al.[2] that fusional vergence responses were slightly less than their stimuli and this lag increased for larger fusional vergence stimulus. Similar effect was observed also by Jones[40]. There are some limitations of visual system to what extent the lag of vergence response can be tolerated by binocular system. This limitation is closely related to the size of receptive fields and fusion. If a lag of increasing vergence step response at 400 ms nonius delay is larger as the receptive fields can tolerate at central retinal area, we can observe worsening of vergence step response with increasing step stimulus size.

Fredenburg and Harwerth[24] did not observe any significant changes in the vergence step response by changing stimuli size neither for convergent, nor divergent vergence step responses. They used a longer presentation time of nonius lines – 250 ms (we used 80 ms). Thus, it could be possible vergence response becomes more stable and independent of vergence step stimulus size with increasing stimulus appearance duration. As one of our participant showed no influence of step stimulus size on vergence response pattern even with a small stimulus presentation time (80 ms), smaller presentation times could easier differentiate persons with good and poor vergence step responses.

There was a different effect of viewing distance and disparity step stimulus size on convergence and divergence responses. Also previous researches[24,40,49,50] showed that mechanisms for convergent and divergent responses are a bit different. Thus, if there are different perception and realization mechanisms proved by brain function analyses and also by different training facilities for crossed and uncrossed disparities, they should be analyzed separately.

For example, more participants had effect of distance on divergence response then convergence response. It correspond to the observations described previously by Alvarez et al.[49] They observed that divergence response on step stimuli is depending on initial vergence angle, but convergence show no such effect. They used distances expressed in degrees – 20º, 16º, 12º, 8º, and 4º (in average 17, 22, 30, 45, 90 cm). The divergence responses showed smaller latencies and greater peak velocities to stimuli near the participant compared with responses to stimuli far from the participant. At close distances (16º and 20º), convergence and divergence had relatively similar peak velocities. But at larger distances (especially 4-8º), convergence becomes approximately twice as fast as divergence. Accordingly, we expressed our viewing distance in degrees (30, 40, 60, 100 cm corresponds to 12º, 9º, 6º, and 3.5º, respectively; taking into account the mean interpupilary distances of participants). Thus, we mostly operated at the distances were asymmetry of vergence movement must be observed. And most of our participants showed statistically significant changes of vergence response depending on the viewing distance (see Table 4.5). But if we looked on the changes of maximal velocities for convergence, divergence, and the asymmetry of maximal velocities (calculated as a difference between velocities: V_{conv} + V_{div}), there were no effect of the distance for a group means (see Figure 4.8).

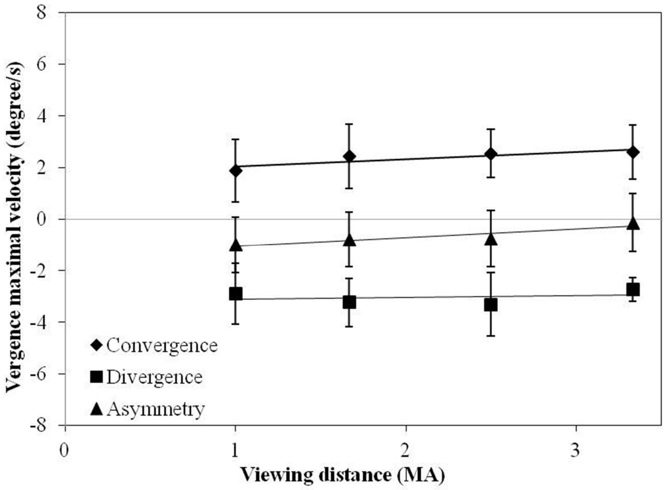

Figure 4.8. Maximal vergence velocities for convergence, divergence and their asymmetry (V_{conv} + V_{div}) as a function of viewing distance (group mean ± standard deviation).

We used Friedman test to see the effect more clearer. For the group of 7 participants, the vergence velocities and asymmetry did not change with increasing viewing distance (Friedman test: $F_{conv} = 1.50$; $p = 0.2$; $F_{div} = 1.35$, $p = 0,3$; $F_{asym} = 1.82$, $p = 0.2$).

Alvarez et al.[49] observed also that divergence latency increased at larger distances (4-8°) compared to convergence latency. If there is larger latency of the movement, maximal vergence velocity will also appear later. Using nonius method, we were not able to obtain the latency of vergence movement but we could evaluate the moment in time (interval) when the maximal vergence velocity was observed. The maximal vergence velocity was estimated as a maximal change in vergence response for three 100 ms intervals (100 vs. 200 ms, 200 ms vs. 300 ms, and 300 vs. 400 ms). The time interval, when maximal convergence velocity appeared, varied for all participants and did not show any relation to the viewing distance (Friedman test: $F_{conv} = 2.93$; $p = 0.06$). However, maximal divergence velocity was observed earlier for closer distances and later as the viewing distance increased to 100 cm (Friedman test: $F_{div} = 3.48$; $p = 0.04$). Thus, our findings correspond to the findings of Alvarez et al.[49] in that the time to maximal divergence velocity is longer at larger viewing distance (or smaler initial vergence angle).

Rashbass and Westheimer[39] observed some relationship between size of the step stimuli and vergence response. Decreasing the vergence step stimuli, an overshoot in one direction was observed (especially for 20 min arc step stimulus size). Corrective movement was also observed afterwards to correct this overshoot and bring eyes closer to fixation position. At the same time, the larger movements were slowed relatively earlier in their course and reached their final level asymptotically. Despite this difference in vergence dynamics, they observed that the amplitude of the vergence movements matched the target very well (the final disparity did not exceed a few min arc). A similar effect was observed also by Cornell et al.[51]. They examined the accuracy of vergence response for near and far fixations. They observed that divergence response on 10º vergence stimulus is smaller (less accurate) at 200 cm viewing distance. Additionally, the overconvergence was observed at 30 cm viewing distance. Largest vergence errors appeared for divergence with fast and large increase of viewing distance. In addition, peak velocity of divergence was smaller and its latency was larger than for convergence. But they also doubt that vergence response is always depending on initial stimulus position. At larger distances, eyes are a bit in converging position. Thus, convergence response can be easier and faster from larger distances, but divergence movement – harder and with longer latency.

Both convergence and divergence was varying with increasing disparity step stimulus size. Their maximal velocities also increased as the disparity stimulus step size became larger (see Figure 4.9) (Friedman test: $F_{conv} = 14.42$, $p < 0.001$; $F_{div} = 116.50$, $p < 0.001$). The velocities became more variable between participants at larger step stimulus sizes (especially for 120 min arc stimulus size) as showed by standard deviation. Thus, it agrees with our observation that it is harder for participants to keep good vergence response at larger stimulus sizes in virtual stimulus presentation where LC shutter glasses are used to separate images of both eyes. This performance depends on the individual quality of vergence movement. The time of maximal convergence velocity appearance varied for all participants and did not show any relation to the step stimulus size (Friedman test: $F_{conv} = 2.06$; $p = 0.1$) compared to divergence – maximal divergence velocity was observed earlier for smaller step stimulus sizes (except participant S1) and later as the step stimulus sizes increased (Friedman test: $F_{div} = 52.63$; $p < 0.001$).

Despite different performance features for convergence and divergence, the asymmetry of maximal vergence velocity shows no changes at different step stimulus sizes (Friedman test: $F_{div} = 0.50$; $p = 0.7$) for a group mean (see Figure 4.9). Similar as we observed for maximal vergence velocities, the asymmetry of maximal velocities also shows larger variance with increasing step stimulus size (see standard deviations in Figure 4.9). Some shows an increase of the asymmetry in convergence direction (like participant S7), and some shows an increase of the asymmetry in divergence direction (like participants S1 and S4). The rest of participants show no changes of asymmetry of maximal vergence velocities. There is an inter-individual difference between participants.

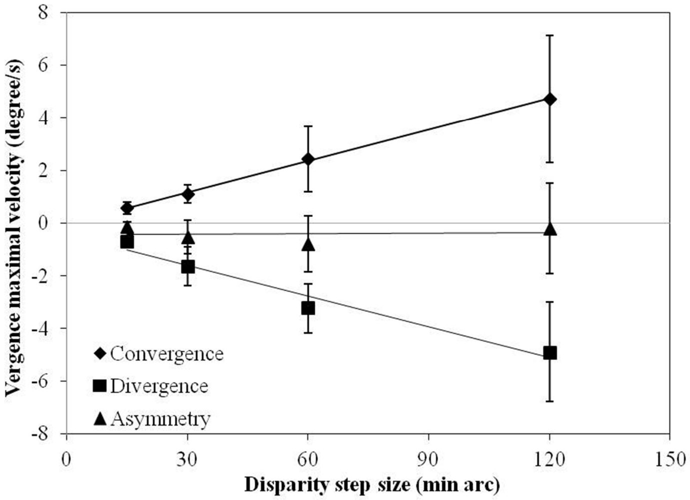

Figure 4.9. Maximal vergence velocities for convergence, divergence and their asymmetry (V_{conv} + V_{div}) as a function of disparity stimulus step size (group mean ± standard deviation).

Thus, asymmetry of maximal vergence velocities did not changed with viewing distance, nor with disparity step stimulus size. That could explain flat curves for predictor of fixation disparity and weak correlation between measured fixation disparity and predictor of fixation disparity. Thus, not only asymmetry of vergence velocities determines fixation disaprity of the person. There must be other factors influencing the size and direction of fixation disparity.

When we change fixation from distance to near, not only vergence is changed but also accommodation that influences dynamic vergence response amplitude via accommodative vergence. The equation (see Eq. 3.1) we use to calculate predictor of fixation disparity does not contain the accommodation factors. Patel et al.[23] excluded accommodation from the primary analyses of fixation disparity origin in neural network model assuming open-loop accommodation system. As Patel et al.[23] observed and described in his work, previous studies (like a study of Semmlow and Hung[52]) showed that the slope of the relationship between fixation disparity and vergence demand is modified when accommodation operates in open- versus closed-loop condition. The slope of prism induced fixation disparity curve becomes shallower when accommodation operates in open-loop compared to closed-loop condition, and their data are consistent with current models of accommodation and vergence[18,23,53]. In comparison to Semmlow and Hung's data[52], Patel et al.[23] describes also results of Hessler, Pickwell, and Gilchrist[54]. They showed that "the slope of fixation disparity curve becomes steeper when accommodation operates in open-loop compared to closed-loop condition". Thus, Patel et al.[23] concluded, "regardless of the actual sign of the change in slope, one can determine the fixation disparity curve under a closed-loop accommodation condition from that under the open-loop accommodation condition by adding a term, $FD(V, A) = E(V)+\alpha V+\beta A+\delta$, where α represents the change in slope of the fixation disparity curve from the closed-loop to open-loop accommodation condition, β represents the shift in fixation disparity curve due to accommodation, δ is a constant bias, and A is the accommodation demand and V is the vergence demand." This analysis is just approximation and assumes linear correlation between the accommodation and the vergence systems. Ogle et al.[2] showed that for many subjects, the fixation disparity curves did not merely shift but also changed shapes when accommodation changed from far to near and vice versa. This phenomenon cannot be explained by linear interactions of vergence and accommodation and points to a severe limitation of existing models of accommodation and vergence." On the end Patel et al.[23] concludes that "a more formal and accurate analysis based on our model requires a complete neural network model of accommodation and vergence."

From our results it is seen, that such accommodation exclusion will decrease possible explanation of fixation disparity with the neural network model. In feedback control theory based models accommodation is still involved and better describes real vergence behavior. All this predicts that accommodation cannot be excluded from vergence model even using dynamic neural network model.

Patel et al. [23] have mentioned the possible influences of different other factors: vergence adaptation, proximal cues, viewing distance, heterophorias, and dark vergence. But they supposed that observing the fixation disparity "under conditions that eliminate (or keep fixed) the before mentioned parameters (i.e., in the absence of adaptation, for stimuli without proximal cues, when accommodation input and viewing distance are kept constant), these are modulatory effects, rather than being the basic neural origin of fixation disparity. These factors may affect fixation disparity indirectly via changes in vergence dynamics". There are father researches needed to discuss the relative contribution of these modulatory factors in determining vergence dynamics and fixation disparity. Following these considerations, further experiments should be done analyzing the influence of other factors not only the asymmetry of vergence velocities on the origin of fixation disparity.

4.6. Conclusions II

1. Our results, obtained with nonius technique, replicates previous objective recordings:
    - the vergence velocity and also the amount of vergence response (min arc) increases with the size of the step stimulus,
    - the lag of vergence response increased for larger vergence stimulus sizes,
    - the moment in time when maximal divergence velocity is observed is increasing with larger viewing distance or smaller initial vergence angle.

    Thus, the subjective method with dichoptic nonius lines can be used to provide physiologically plausible estimation of individual differences in dynamic asymmetry of vergence.
2. Our results demonstrate, that the most adequate vergence performance (i.e. the vergence response amplitude that mostly reach the stimulus amplitude) can be achieved using 60 min arc step stimulus size and closer viewing distances (up to 60 cm). With larger vergence step stimuli, this relative vergence response (in percents of step stimulus) deteriorates. To not produce artificial vergence problems, these parameters of vergence step stimulus presentation would be more appropriate for clinical purposes using nonius technique with LC shutter glasses to predict possible vergence problems.
3. Our results replicate previous observations that the subjectively measured fixation disparity shows significant changes with viewing distance (more exo (eso) at closer (at larger) viewing distances). However, our results did not confirm this observation for the predictor of fixation disparity. Thus, the asymmetry of the vergence maximal velocities is not the only factor to be used to explain fixation disparity using the neural network model described by Patel et al.[23]. Some additional factors (accommodation, dark vergence etc.) should be used to better predict fixation disparity.

5. A multiple regression model to explain inter-individual differences in subjective fixation disparity (Experiment III)

5.1. Purpose of the Experiment III

The aim of Experiment III was to compare fixation disparity and vergence step response obtained both with nonius technique and with eye tracker. Thus, we evaluated the precision of both techniques in a group of randomly chosen participants. Additionally we investigated to what extent the inter-individual variability of subjectively measured fixation disparity can be explained by combination of underlying physiological mechanisms as vergence step response asymmetry, dark vergence, heterophoria, and nonius bias.

5.2. Participants III

The sample group contained 20 participants (mean age 24.5 ± 4.3 years; range 16 to 34 years) in the experiment III. All participants were screened to include only those with normal monocular and binocular visual acuity (1.0 or more in decimal units) at a distance (5 m) and at the test viewing distance (60 cm). The participants were emmetropic (both sphere and cylinder in a range of ±0.5 D), except for one participant (-2.0 D myopia in both eyes), who wore contact lenses during testing. All participants had binocular single vision and good stereovision at 5 m (Polatest, Zeiss, Oberkochen, Germany) and 40 cm (TNO, Lameris Ootech, Nieuwegein, the Netherlands), in both the crossed (67.5” ± 44.5”) and uncrossed (82.5” ± 49.5”) direction. The experiments were undertaken with the written consent of each participant. The procedures of the present study were approved by the ethics review board of the Leibniz-Institut für Arbeitsforschung an der TU Dortmund and followed the tenets of the Declaration of Helsinki.

5.3. Experimental design III

All participants had three repeated sessions on separate days. Each session comprised two parts of measurements:

1) vergence disparity step response measurements for 5 lengths of nonius delays, including both convergent and divergent directions;
2) three fixation disparity measurements.

The session always started with a vergence response measurement (randomly varied amounts of nonius delay). Fixation disparity was measured at the end of each session after a rest of about 10-15 min. In parallel with subjective estimation of fixation disparity and disparity vergence step response, objective eye movement tracking was performed using the video-based EyeLink II. Each session took about 1.5 hours, including rests. Periods of near vision did not occur, thus did not induce vergence adaptation. For data analyses, we used statistics available on Free Statistics Software[55], R software, MatLab, Microsoft Excel, Origin, and MedCalc.

5.4. Results III

5.4.1. Reliability of vergence response measurements using eye tracker

To analyze vergence step response measured objectively with eye tracker, we used averaged results from all useful epochs for each repeated session (see Figure 5.1). We could observe different vergence step response patterns – stronger or weaker in both directions (see Figure 5.1A) or poor (if none) in one direction (see Figure 5.1B).

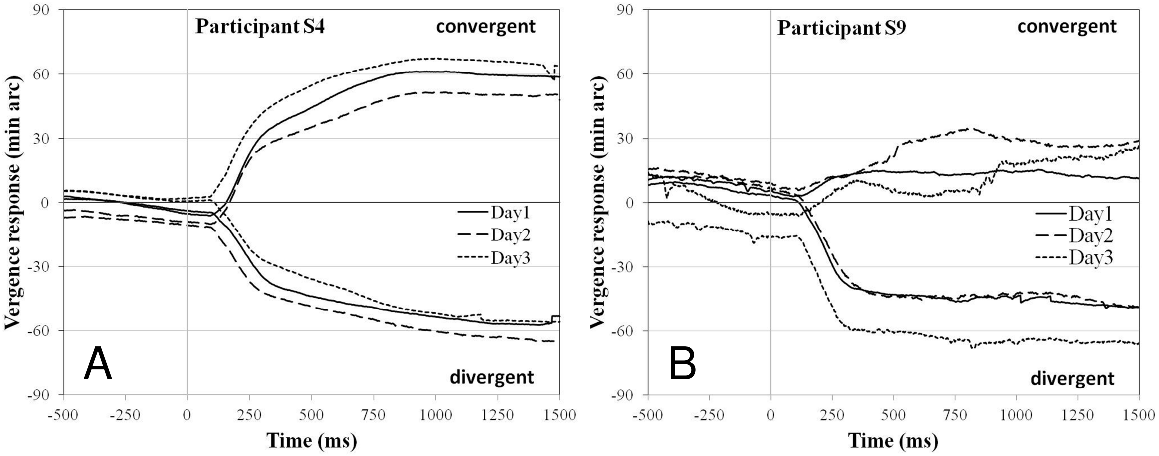

Figure 5.1. Examples of vergence response for two participants measured objectively with eye tracker for each session (Day 1, Day 2, Day 3). A. Participant S4 shows good vergence step response both in convergent and divergent direction during all sessions. B. Participant S9 shows good divergence step response, but poor convergence step response during all sessions.

In Experiment I and Experiment II, we used maximal vergence velocity and the dynamic asymmetry obtained subjectively with nonius lines (see Eq. 3.2). Therefore, we looked now on the maximal vergence velocity obtained from objective measurements. We calculated velocity profiles for each epoch with a two-point central difference algorithm[56] incorporating a central difference of ±1 sampling interval of 4 ms (see Figure 5.2). After 10 Hz low-pass filtering, the smoothed data were scanned for the maximum objective velocity within a time interval of 100 to 500 ms after the onset of the disparity vergence step stimulus (see Figure 5.2). The average of all maximal velocities was then calculated from all useful epochs. This calculation takes into account the variation of inaccuracy of calibration and the variation of repetition of measurements.

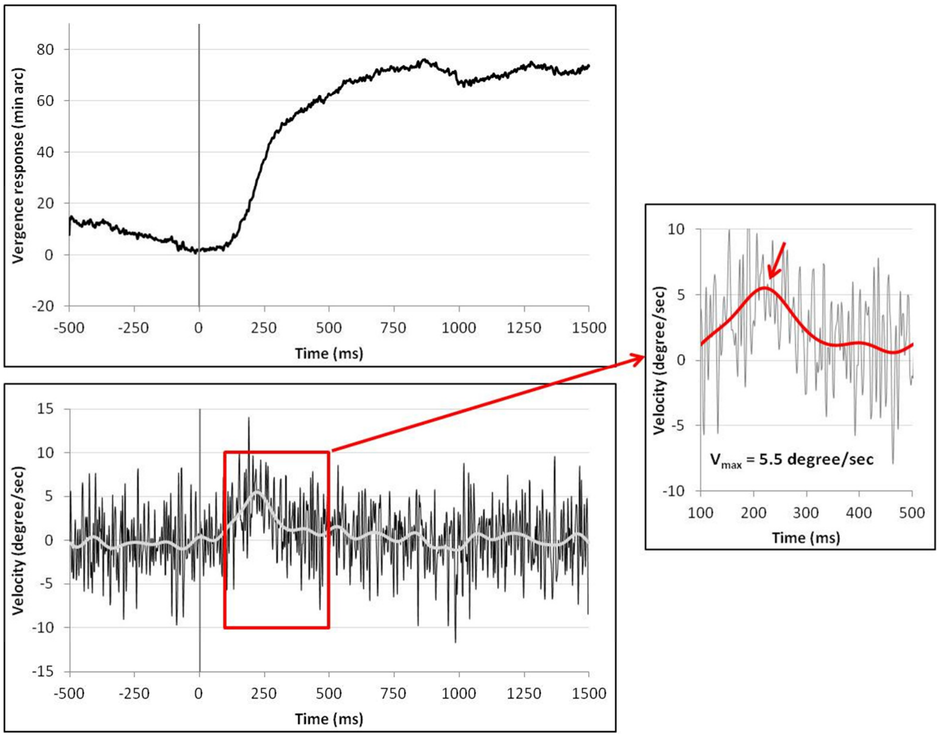

Figure 5.2. Example of maximal vergence velocity calculation for objectively measured vergence step response. Upper figure shows convergence response during 2 s interval (one epoch). Lower figure shows the vergence velocity calculation with a two-point central difference algorithm[56] incorporating a central difference of ±1 sampling interval of 4 ms. Grey line (in the lower figure) and red line (in the figure to the right) represents vergence velocity pattern after 10 Hz low-pass filtering. With a red square, we show the time interval (also presented in the figure on the right) within which maximal vergence velocity was scanned. With the small red arrow, the point in the line is shown where maximal vergence velocity appears. In a given example, maximal vergence velocity was 5.5 degree/sec.

The test-retest correlations of vergence velocity among different sessions were between 0.62 and 0.91 (see Figure 5.3). Regarding the difference between velocity measures between two sessions, the range of ±1.96 SD was ±2.23 degree/sec and ±1.02 degree/sec for the convergent and divergent velocity, respectively, as found in Bland-Altman analyses. Thus, individual differences in vergence velocity could be measured reliably.

Despite vergence velocity calculations showed high reliability, there were non-random, systematic changes in dynamic asymmetry of vergence velocities (A) from session to session shown by a correlation of differences between sessions in the series of three days (A1, A2, A3), since the correlation between (A3 - A1) and (A2 - A1) was significant ($r = 0.69$; $p < 0.001$, $n = 20$). This is a partial correlation analysis made to remove the common variance due to A1 included in these two differences. Thus, these changes in dynamic asymmetry were reliably observed in session 2 and session 3, however they were partly in opposite directions (positive or negative) in different observers.

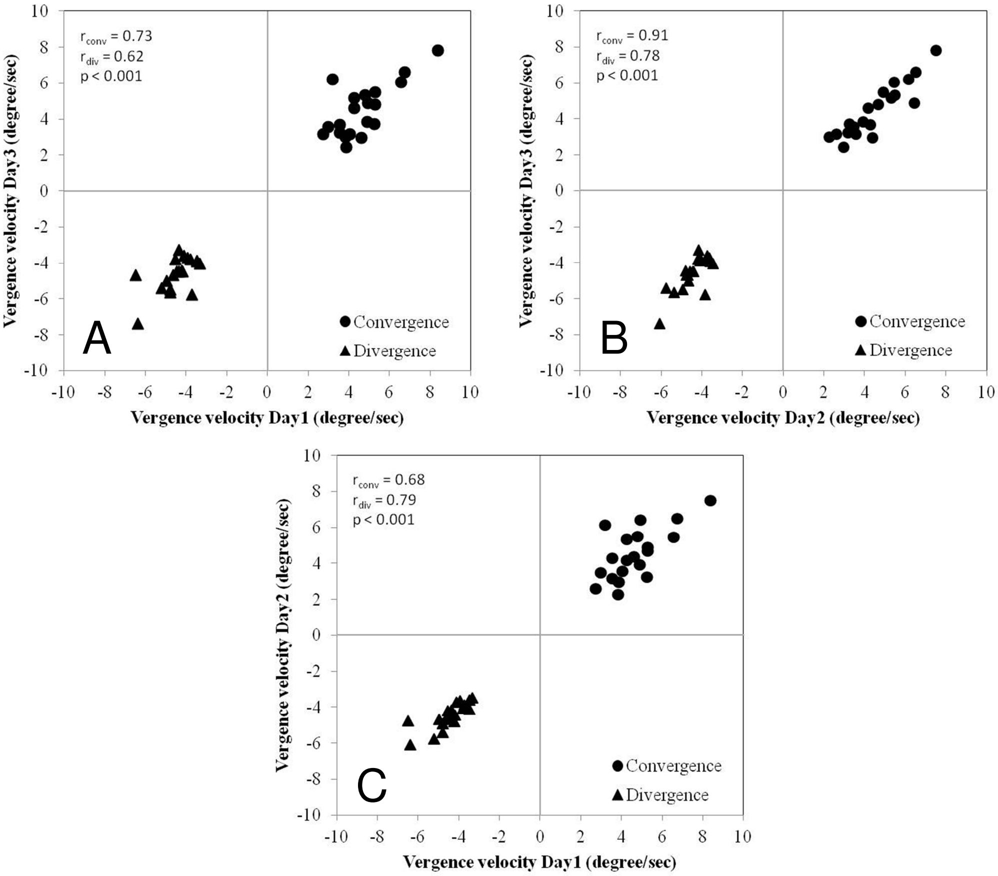

Figure 5.3. The test-retest correlation for maximal vergence velocity calculated from objectively measured vergence step response data: A. Day1 versus Day2, B. Day2 versus Day3, C. Day1 versus Day3.

This shows that in the series of the tree days some subjects changed the asymmetry towards predominance in convergence, while others towards predominance in divergence. This is evidence that training effects in a series of tests are different for the convergence and divergence mechanism. This finding is in conflict with the purpose of the study aiming to explain inter-individual differences in subjective fixation disparity as clinically measured with short test procedures not affecting the measured value itself. Therefore, the present analyses used data from session 1 reflecting the natural vergence state, which can be assumed not (or only minimally) to be affected by training effects of the test procedure itself.

5.4.2. Subjective versus objective measurements of vergence response

To compare with subjective data, objective vergence response was calculated at each time moment (n-1, n, n+1 for 0 ms, 100 ms, 200 ms, 300 ms, and 400 ms) of nonius lines presentation. The "best fit" between subjective and objective data was calculated using cross-correlation from 4 values. It calculates the cross-correlation coefficient at 0 ms shift and maximum correlation at appropriate shift.

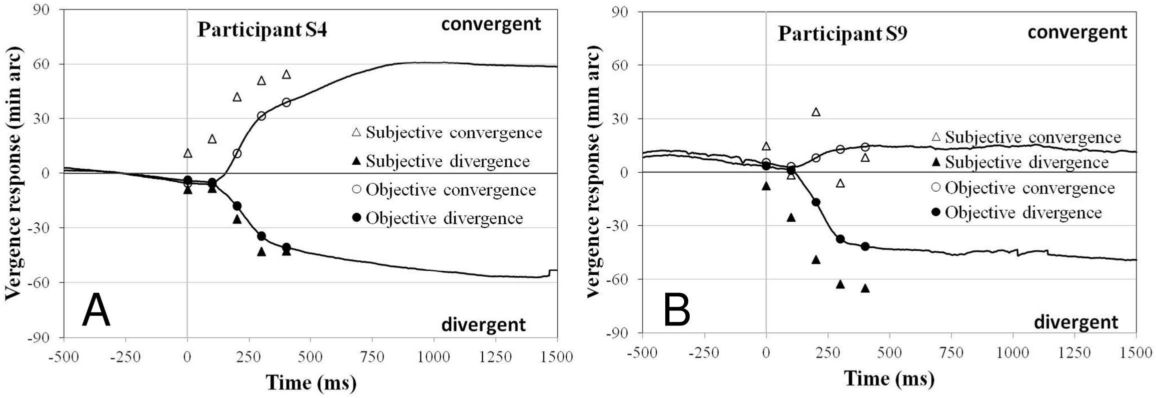

Figure 5.4. Objective and subjective measurements of vergence step response for two participants. Open symbols are showing convergent response, closed symbols are showing divergent response. A. Participant S4 shows good vergence step response and high cross-correlation (r = 1.00 ± 0.00) both in convergent and divergent direction. B. Participant S9 shows good divergence step response and high cross-correlation (r = 1.00 ± 0.00), but poor convergence step response and low cross-correlation (r = 0.22 ± 0.44). Subjective data points are plotted at the moments in time when nonius lines were presented. Continued lines show the whole vergence step response (convergent and divergent) measured objectively with eye tracker.

In Figure 5.4, we plotted objective and subjective vergence response at the moments in time of nonius line's onset. There is constant shift of subjective data to the left. Jainta et al.[31] described similar tendencies and observed high correlation between both results. There should be kept in mind that subjective method does not measure vergence response at given moment of time. There always will be a shift of subjective results from objective ones. The period of time required for retinal and central visual processing until nonius lines are perceived did not match with the time when nonius lines are presented. During this perceptual period, the vergence movement is still proceeding. Thus, nonius test measure the vergence state a certain period τ later than nonius onset. This amount of time shift is unknown and may differ between individuals. The cross-correlation used to compare results from subjective and objective methods takes into account such time shift, comparing only the form of step response, irrespective of any possible factors or amplitude offset between the subjective and objective responses.

Our results replicate results of Jainta et al.[31]. There was high cross-correlation between both vergence step response profiles: the maximum correlation was from 0.22 to 1.00 (mean ± SD: 0.88 ± 0.21) for convergence and from 0.91 to 1.00 (0.99 ± 0.02) for divergence. The lowest cross-correlation coefficients of convergence are observed in subjects having poor vergence step performance (see figure 5.4B). Time shift τ between the subjective and objective profile was 52 ± 40 ms for convergence and 56 ± 35 ms for divergence response in a group of 20 subjects. Overall, intra-individual τ variation was smaller than variation in the group (from 2 ms up to 120 ms).

Jainta et al.[31] showed that the maximal vergence velocity was well correlated between both methods, despite subjective method showed a clear underestimation for both vergence directions. The possible explanation of this underestimation was the sampling interval of 100 ms. Maximal vergence velocity for subjectively measured vergence response was found as a maximal slope from three pairs of nonius delays: 100-200, 200-300, 300-400 ms. These 100 ms intervals probably was too large to detect the moment of time, when maximal velocity appeared. Our results showed low and not significant correlation between both vergence velocity estimation techniques ($r = 0.22$ and $r = 0.44$, for maximal velocities of convergence and divergence, respectively). This difference between our results and results of Jainta et al.[31] could be explained with the stimulus step size. Jainta et al.[31] used the disparity step stimulus of 3°, whereas, we used only 1°. Larger stimulus sizes give larger and more pronounced vergence response values in time. Thus, it is easier to observe differences between subjectively obtained vergence velocities in 100 ms intervals and to get vergence velocity values closer to those, evaluated with objective methods.

Maximal vergence velocities, calculated from subjectively measured data, showed low and not significant test-retest correlations among different sessions (0.35-0.46 and 0.07-0.17 for convergence and divergence, respectively). Following all this analyzes, we used maximal vergence velocity obtained from objective data for our further calculations.

5.4.3. Subjective versus objective measurements of fixation disparity

At session 1, only 16 participants showed useful objective fixation disparity data. It varied from about 20 min arc exo up to 15 min arc eso. It was in a range of typical amounts for subjectively measured fixation disparity as mentioned previously in the literature[1-2], but still larger then subjectively measured fixation disparity in our study. Subjectively measured fixation disparity varied only in a range of about 4 min arc exo and 5 min arc eso. There was low correlation, but just significant (r^2 = 0.25, adj. r^2 = 0.20, r = 0.50, p = 0.047, n = 16) between objectively and subjectively measured fixation disparities (see Figure 5.5A).

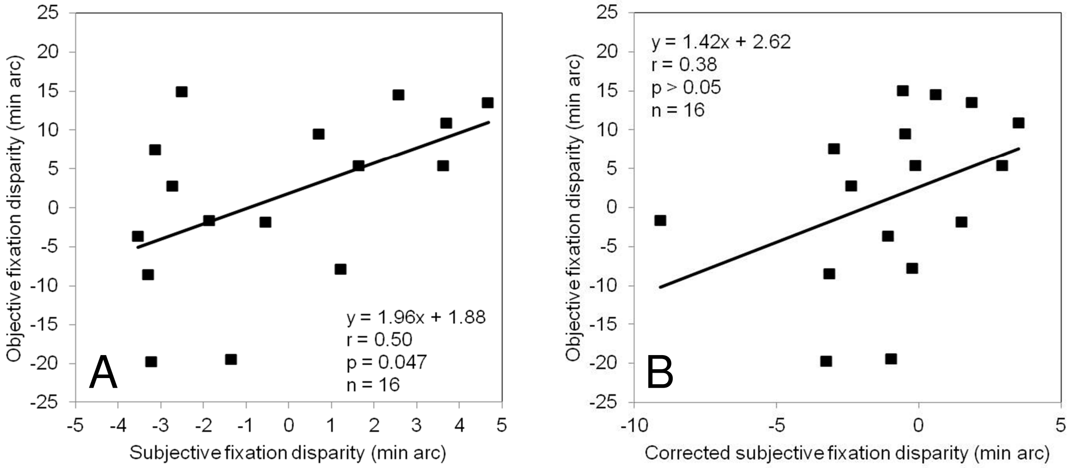

Figure 5.5. Regression between objective fixation disparity and subjective fixation disparity (A) and corrected subjective fixation disparity (B).

Figure 5.5 resembles previous results of Jaschinski et al.[14]. They used nonius bias to correct subjectively measured fixation disparity and observed higher and marginally significant correlations between subjective fixation disparity (SFD) corrected by nonius bias (NB) and objective fixation disparity. Repeating similar analyzes, we calculated corrected subjective fixation disparity (SFD_{cor} = SFD – NB). We did not observe any significant correlation between these corrected subjective fixation disparity and objective fixation disparity (see Figure 5.5B). In addition, correlation coefficient even decreased.

5.4.3. Predictor of fixation disparity using dynamic asymmetry, dark vergence, and nonius bias

In a first approach, we tested whether inter-individual variability in subjective fixation disparity could be explained by dynamic asymmetry, dark vergence (quantified as a resting vergence measurement), and nonius bias. Analysis showed that the data of one participant

(S11) violated the normal distribution for nonius bias (7 min arc). This was not a measurement error, because repeated measurements yielded similar results. For statistical analyses, we were required to exclude this participant because inclusion would have violated the assumption of normal distribution. Thus, we included 19 participants in subsequent analyses.

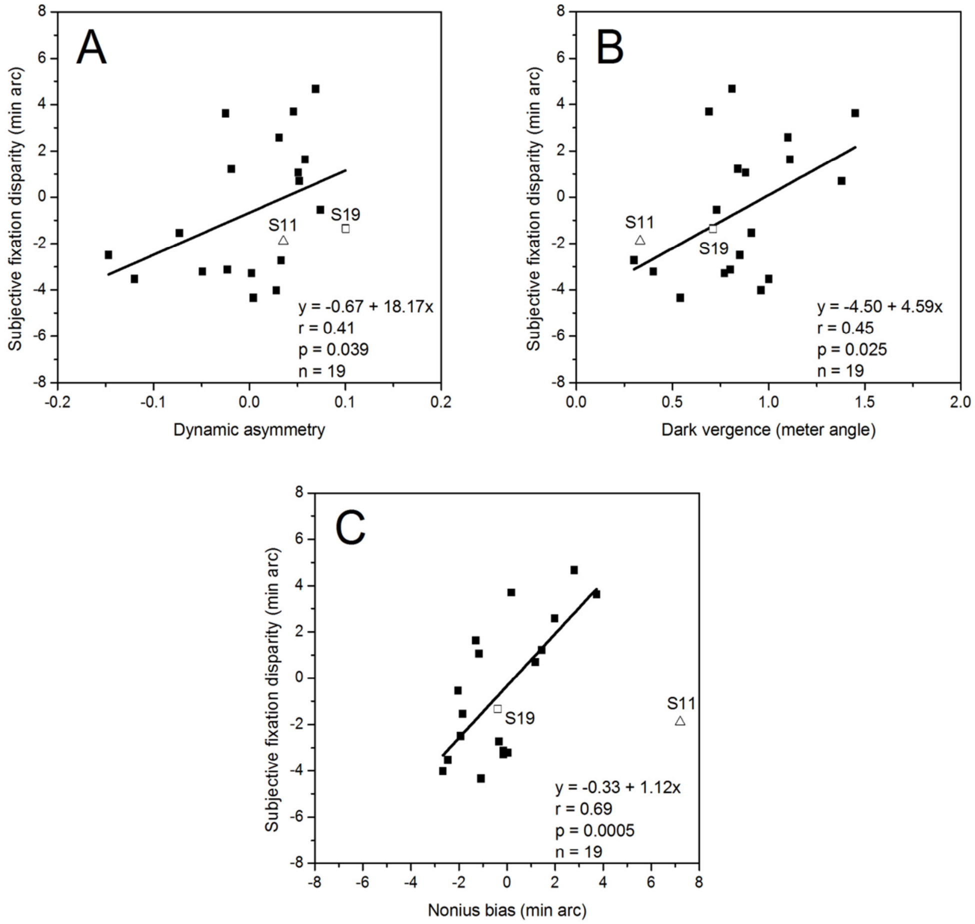

Figure 5.6. Correlation between subjective fixation disparity and (A) dynamic asymmetry of maximal velocities, (B) dark vergence, and (C) subjectively measured nonius bias. Open triangles show data for participant S11, who had an extreme nonius bias and was not included in these correlations or the corresponding multiple regression analysis. Open squares show data for participant S19, who had an extreme exophoria (3.8 degree) and was still included in the present correlations. Reprinted from Investigative Ophthalmology and Vision Science, 52, A.Švede, J.Hoormann, S.Jainta, W.Jaschinski, Subjective fixation disparity affected by dynamic asymmetry, resting vergence, and nonius bias, 4356-4361, Copyright (2011), with permission from ARVO.

In the present study, we used equation 3.2 to calculate dynamic asymmetry. In

Experiment I (similar as Patel et al.[23]), the baseline vergence (BV) state was used to calculate the magnitudes of the effective disparity stimuli, which were 1° - BV and 1° + BV for convergent and divergent stimuli, respectively, and dynamic asymmetry was calculated by weighting the gain factors: $G_{conv} = V_{conv}/(1° - BV)$ and $G_{div} = V_{div}/(1° + BV)$. This, however, tends to artificially increase the correlation between fixation disparity and dynamic asymmetry (following Eq. 3.1), because fixation disparity itself is correlated with baseline vergence. Thus, excluding baseline vergence from calculations, it leads to a more conservative estimation of the correlation of fixation disparity with dynamic asymmetry.

Table 5.1

Results of simple correlation and multiple linear regression explaining the inter-individual variability of subjective fixation disparity by combining the following three factors: dynamic asymmetry, dark vergence, and nonius bias.

Factors	Subjective fixation disparity (n = 19)				
	Simple Correlation		Multiple Linear Regression $r^2 = 0.62, p = 0.002$		
	r	p (1-tail)	Parameter	t-value	p (1-tail)
Intercept			-3.04	-1.97	0.034
Dynamic asymmetry	0.41	0.039	12.96	1.79	0.047
Dark vergence	0.45	0.025	3.03	1.78	0.048
Nonius bias	0.69	0.0005	0.85	3.01	0.004

The relation of all three factors with subjective fixation disparity was analyzed in two steps. First, we tested the relation separately for each factor (see Figure 5.6 and Table 5.1). The correlations ranged from 0.41 to 0.69 and were statistically significant ($p < 0.05$; n = 19). The strongest correlation was observed for nonius bias. Fixation disparity was not significantly correlated with each velocity alone (r = 0.29 for convergence and r = 0.16 for divergence, respectively, n = 19), rather the balance between both was relevant.

Second, using multiple linear regression analyses, we tested all three factors as predictors of subjective fixation disparity. Multiple linear regression analyses require that the factors included are independent. We generally found low and insignificant inter-correlations: dark vergence versus nonius bias r = 0.31 (p = 0.10; n = 19), dynamic asymmetry versus nonius bias r = 0.25 (p = 0.15; n = 19), dark vergence versus dynamic asymmetry r = 0.03 (p = 0.44; n = 19).

The complete multiple regression model in Table 5.1 shows that the three factors had significant coefficients and explained 62% (r = 0.79, p = 0.002; n = 19) of the inter-individual differences in subjective fixation disparity. We calculated a further multiple regression model to determine the extent to which the subjective fixation disparity could be explained by the characteristic factors of physiological vergence alone and found that 39% (r = 0.63, p = 0.02; n = 19) was due to dynamic vergence and dark vergence. An additional 23% of variance was due to subjective nonius bias, an aspect of the subjective measurement procedure.

5.4.4. Predictor of fixation disparity using dynamic asymmetry, heterophoria, and nonius bias

In a second approach, we tested the hypothesis that inter-individual variability of subjective fixation disparity could be explained by dynamic asymmetry, heterophoria (as another measurement of resting vergence), and nonius bias. All three factors were measured during the experimental procedure (despite dark vergence which was measured before experimental procedure).

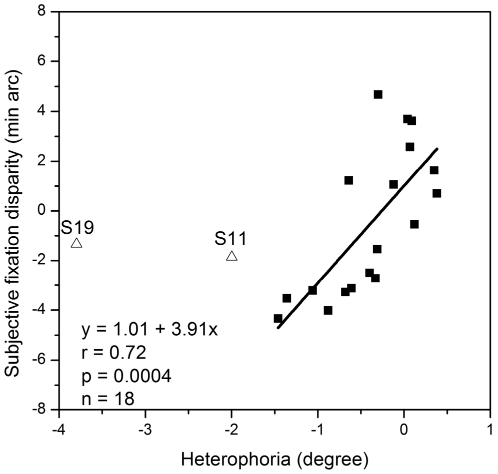

Figure 5.7. Correlation between subjective fixation disparity and heterophoria. Open triangles show data for two participants not included in the correlation. Participants S19 and S11 were outliers with respect to heterophoria and nonius bias, respectively. Reprinted from Investigative Ophthalmology and Vision Science, 52, A.Švede, J.Hoormann, S.Jainta, W.Jaschinski, Subjective fixation disparity affected by dynamic asymmetry, resting vergence, and nonius bias, 4356-4361, Copyright (2011), with permission from ARVO.

A check of the normal distribution showed that the data of one additional participant led to a violation of the normal distribution for heterophoria (S19: 3.8 degree exophoria). This was also not a result of measurement errors, but rather, the particular condition of this observer, as confirmed by repeated measurements. For statistical analyses, we were required to exclude this participant in order to meet the assumption of normal distribution. Thus, 18 participants were included in subsequent analyses.

We observed insignificant correlations between dynamic asymmetry versus nonius bias $r = 0.27$ ($p = 0.14$; $n = 18$) and heterophoria versus nonius bias $r = 0.35$ ($p = 0.08$; $n = 18$), but heterophoria and dynamic asymmetry $r = 0.51$ ($p = 0.02$; $n = 18$) were significantly correlated. Thus, three factors were not independent and therefore multiple linear regression analysis using all three factors was not possible.

As heterophoria alone was significantly correlated with subjective fixation disparity: $r = 0.72$ ($p = 0.0004$, $n = 18$) (see Figure 5.7), we calculated a further multiple regression model to determine the extent to which the subjective fixation disparity could be explained by heterophoria and subjective nonius bias.

Table 5.2

Results of simple correlation and multiple linear regression explaining the inter-individual variability of subjective fixation disparity by combining heterophoria and nonius bias.

Factors	Subjective fixation disparity (n = 18)				
	Simple Correlation		Multiple Linear Regression $r^2 = 0.74$, $p < 0.0001$		
	r	p (1-tail)	Parameter	t-value	p (1-tail)
Intercept			0.80	1.67	0.12
Heterophoria	0.72	0.0004	2.96	3.84	0.002
Nonius bias	0.69	0.0005	0.81	3.53	0.003

The complete multiple regression model in Table 5.2 shows that those two factors had significant coefficients and explained 74% ($r = 0.86$, $p < 0.0001$; $n = 18$) of the inter-individual differences in subjective fixation disparity. Thus, it is by 12% more than we observed using vergence dynamic, dark vergence and nonius bias.

5.5. Discussion III

If we take the neural network model predicted by Patel et al.[23], dynamic asymmetry of vergence step response is the most significant factor explaining the origin of fixation disparity (either there will be exo, eso or zero fixation disparity). Following this model, a given target disparity activates more than one disparity detector; due to the broad tuning of disparity detectors, a spatially distributed disparity code will be exited. For the case of fixation disparity, a stationary fusion stimulus will activate also detectors corresponding to small convergent and divergent disparity. If the motor activity in these two directions balances each other, the fixation disparity is zero, but any asymmetry between the convergent and divergent activity will result in a fixation disparity. The activity of the opponent pathways is characterized by corresponding gain factors. Consequently, fixation disparity is predicted from the asymmetry in convergence and divergence sensory motor gains (G_{conv}, G_{div}), i.e., fixation disparity is proportional to the function shown in equation 5.1.

$$FD_{pre} \sim (\sqrt{G_{conv}} - \sqrt{G_{div}})/(\sqrt{G_{conv}} + \sqrt{G_{div}}) \qquad \text{Eq. 5.1}$$

We represented gain factors by convergent and divergent velocities ($V_{conv,}V_{div)}$. If we refer to subjective measures of vergence velocity with nonius lines in Experiment I, we explained at most 50% (r^2) of the inter-individual variance in subjective fixation disparity while it was only 2% in the present Experiment III. As baseline vergence alone is highly correlating with subjectively measured fixation disparity, we also tried to exclude it from calculations (see Eq. 3.2). The correlation decreased to 37% in Experiment I and to 1% in Experiment II. It was still statistically significant in Experiment I ($p < 0.01$, one-tailed), however, no effect was observed in Experiment III based on subjective velocities.

To improve our correlation in Experiment III, we used objectively estimated maximal vergence velocity. Despite the data shown by Jainta et al.[31], where subjectively estimated maximal vergence velocity was highly correalted with objective estimation of vergence velocity, the objectiv estimation of vergence velocity is more precise. This improved our fixation disparity prediction based on the dynamic asymmetry up to 17% (r^2, $n = 19$). But still it was smaller than shown in Experiment I. This difference could be explained with the range of fixation disparity. In Experiment I, it varied from about 10 min arc eso to 6 min arc exo (partly due to the selection of participants with large fixation disparities), while in the current random sample the range of observed fixation disparities was smaller (from 5 min arc exo to 5 min arc eso). The range of dynamic asymmetry was also much smaller in the present study (having values in a range from -0.2 to 0.2; in Experiment I – from -1.0 to 1.0), so that overall correlations tended to be smaller. These results show that dynamic asymmetry of vergence response can be one factor explaining the origin of larger fixation disparities but it cannot be efficient for any case.

To improve the prediction of the origin of fixation disparity additional factors should be considered as it was already suggested by Patel et al.[23] and shown by Jaschinski[30]. Therefore, we investigated two additional factors: dark vergence and nonius bias. Subjective fixation disparity was correlated with each of these factors. The combination of all three factors (dynamic asymmetry, dark vergence, and nonius bias) in a multiple regression analysis explained about 62% (r^2, n = 19) of the inter-individual variability in subjective fixation disparity. The multiple regression analysis explained a larger proportion of variance than each factor alone, since the three factors influencing subjective fixation disparity showed smaller inter-correlations. Since data of one of our 20 participants had to be excluded as outlier, our findings refer to a sample of participants with normally distributed data, but not to any observer.

If instead of dark vergence we could use heterophoria in this model, we probably could improve our prediction. Heterophoria is a resting vergence state without a fusion stimulus (open loop condition) but including an accommodative stimulus. Heterophoria is often reported as being related to fixation disparity[3,57,58]. Studies differ in reports of the strength of this correlation, which may depend on viewing distance[58]. There are also cases with different directions of heterophoria and fixation disparity[3,58,59]. However, authors agree that large amounts of fixation disparity are associated with large amounts of horizontal heterophoria. This correlation was also confirmed by objective measures[14].

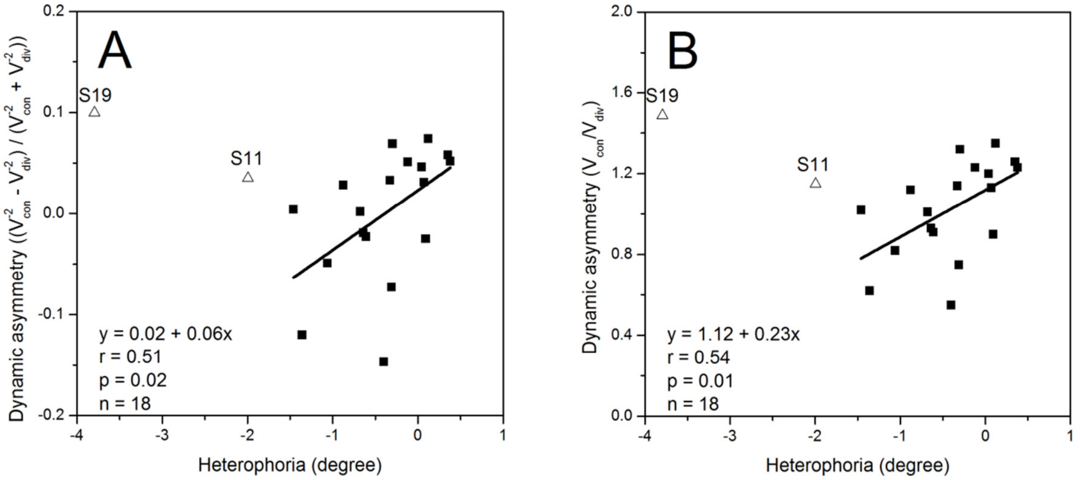

Figure 5.8. Correlation between heterophoria and dynamic asymmetry, calculated as suggested by (A) Patel et al.[23] and (B) Kim et al.[60]. Open triangles show data for two participants not included in the correlations. Participants S19 and S11 were outliers with respect to heterophoria and nonius bias, respectively. Reprinted from Investigative Ophthalmology and Vision Science, 52, A.Švede, J.Hoormann, S.Jainta, W.Jaschinski, Subjective fixation disparity affected by dynamic asymmetry, resting vergence, and nonius bias, 4356-4361, Copyright (2011), with permission from ARVO.

We observed significant correlation between heterophoria and subjective fixation disparity (r = 0.72, see Figure 5.7). Despite this correlation, heterophoria was not included in multiple regression analyses because there was a significant correlation between heterophoria and dynamic asymmetry (r = 0.51). Interestingly, Kim et al.[60] also found a strong correlation between heterophoria and dynamic asymmetry (r = 0.9), defined as a ratio of convergent to divergent peak velocity (V_{conv}/V_{div}). Recalculating this correlation according to the definition of Kim et al.[60], our data still showed high correlation (r = 0.54, p = 0.01) (see Figure 5.8). Interestingly, the dynamic asymmetry was not significantly correlated to dark vergence, the other possible measure for the resting vergence (r = 0.008, n = 18; r = 0.03, n = 19).

The possible reason for a correlation of the asymmetry with heterophoria, but not with dark vergence may lie in the role of accommodative functions that are included in heterophoria but not in dark vergence. Therefore, in addition to dark vergence we should also analyze the effect of accommodation. A full account for accommodation would require measurement of the accommodative response and AC/A ratio and inclusion of these factors in a multiple regression analysis; such accommodative data were not available in the present study. But it would be possible to exclude accommodative factor from existing measurements like heterophoria.

Heterophoria sometimes is described as a result of inadequate or excessive function of the sum of tonic, accommodative, and proximal vergence at near[61]. To compensate heterophoria in binocular condition, fusional vergence is involved. These are vergence components described by Maddox. Tonic vergence (expressed also as dark vergence) is mainly determining vergence position at distance. If the object of interest is moved closer, this produces large disparity on both retinas. To reduce the binocular disparity, fusional vergence (called also disparate vergence) is activated. Schor[16] mentioned the work of Hoffman and Bielschowsky (1900) describing two components of fusional vergence movement: fast and slow fusional vergence. Fast fusional vergence acts quickly to reduce retinal disparity, achieving single vision even within 1 second[37]. However, once fusion is obtained, there is a tendency toward rapid decay of the fast fusional vergence innervation. Consequently, the second system, slow fusional vergence, comes into play to reduce stress on the fast fusional vergence system and to maintain alignment[62]. Slow fusional vergence acts slower and requires about 30 seconds. It is not generated by retinal disparity, because it occurs after disparity is significantly decreased by fast fusional vergence, rather by the output of the fast fusional vergence system. It has long lasting effect producing changes in tonic vergence (vergence adaptation) and supplementing the rapid decay of fast fusional innervations.

Two other components of vergence movement (proximal and accommodative) are activated in parallel with fast fusional vergence. Changes of viewing distance are activating proximal vergence. When stimuli fall on or near the fovea, accommodative vergence is activated. Possible interaction of all four components during different phases of vergence movement is illustrated in Figure 5.9.

In open-loop condition like during heterophoria measurement, vergence position is mainly determined by tonic, accommodative and proximal vergence components. Accommodation is directly related to all those three factors. Thus, the type and size of heterophoria can be characterized by tonic and accommodative factors. This description confirms observation of Jaschinski[30]. He observed that there are three factors predicting heterophoria at 60 cm viewing distance: dark vergence, accommodative gain and AC/A ratio. He also observed that such accommodative components tended to be small and non-significant in multiple regression analyses for fixation disparity; however, these factors may still play a certain role.

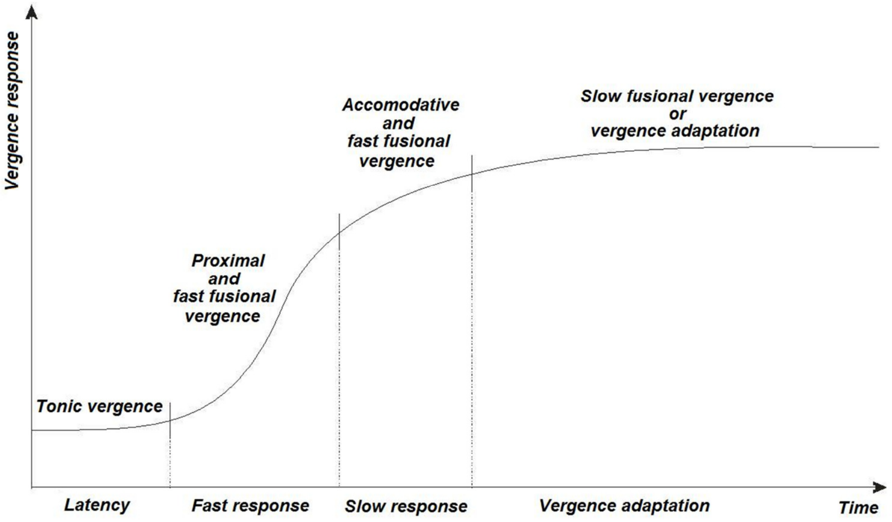

Figure 5.9. Different phases and involvement of vergence components during vergence response

Instead of measuring accommodation, we used heterophoria as a characteristic factor of physiological vergence resulting from combination of dark vergence, accommodative factor and the asymmetry of dynamic vergence response. We could explain now 12% (Multiple Linear Regression: $r^2 = 0.74$) more of the inter-individual differences in subjective fixation disparity as using vergence dynamic, nonius bias, and dark vergence as characteristic factors of physiological vergence (Multiple Linear Regression: $r^2 = 0.62$).

Thus, the present study represents a novel investigation in that: (1) we extracted dynamic asymmetry from objective measures of vergence velocity (while subjective estimations were used in our Experiment I and Experiment II), (2) we additionally included resting vergence (dark vergence) and nonius bias into combined analyses of these three factors, and (3) we included accommodative influence using heterophoria measurements. So far, however, the results of the present experiment suggest that clinically relevant subjective fixation disparity can originate from a combination of independent physiological sources that directly affect fixation disparity, not only via changes in vergence dynamics. The size and type of subjectively estimated fixation disparity is influenced also by the nonius bias, which represents a measurement error due to the method of using nonius lines for testing fixation disparity.

5.6. Conclusions III

1. We demonstrated that the dynamic asymmetry of vergence response, dark vergence, and nonius bias explained at most 62% (r^2) of the inter-individual variance in subjectively measured fixation disparity for a sample of participants with normal distribution of vergence parameters; in this multiple regression analysis, accommodative contributions are not included.
2. We also demonstrated that heterophoria and nonius bias explained 74% (r^2) of the inter-individual variance in subjectively measured fixation disparity; the advantage of this model may be explained by accommodative contributions that are indirectly included in this multiple regression since heterophoria at near depends on accommodation.
3. Our results show that fixation disparity origins from a combination of independent physiological sources. We demostrated that heterophoria measurement combines most of those sources: the dynamic asymmetry of vergence response, dark vergence, and – indirectly – also accommodative contributions.
4. Our results further demonstrated that the size and type of subjectively estimated fixation disparity is influenced also by the nonius bias, which represents a measurement error due to the method of using nonius lines for testing fixation disparity.

Proposed applications

1. The dynamic asymmetry of vergence response is only partly related to the subjective fixation disparity in a larger group of randomly chosen participants. Thus, the neural network vergence model of Patel et al.[23] cannot fully explain the inter-individual variances in subjective fixation disparity.
2. Subjectively measured fixation disparity origins from a combination of independent physiological sources: the highest proportion of explained inter-individual variance was reached with a statistical model that includes (1) heterophoria (comprising the dynamic asymmetry of vergence response, dark vergence, and – indirectly – accommodation factors) and (2) the inevitable measurement error (nonius bias) due to the method of using nonius lines for testing fixation disparity.
3. The subjective method with dichoptic nonius lines provides physiologically plausible estimation of individual differences in dynamic asymmetry of vergence. The most adequate vergence performance (i.e. the vergence response amplitude that mostly reaches the stimulus amplitude) can be achieved using 60 min arc step stimulus size and closer viewing distances (up to 60 cm). A 400 ms nonius delay after the vergence step stimulus onset can be used to evaluate the quality of the vergence step response for subjective measurements. Good vergence responses are characterized as having a relative vergence step response amplitude of at least 60% of the vergence step stimulus size.

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