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Investigating effect of defocus using simple visual reaction times

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Abstract

In this study, simple visual reaction time measurements have been performed to study the monocular and binocular effects of contrast and defocus on visual performance.

The binocular- and monocular (dominant eye) reaction times (RT) from 6 subjects (age: 25-40 years) have been measured for different levels of positive defocus (up to 4.25 dpt) using a 4c/deg, 10% contrast sine grating stimulus. Additionally the same 4c/deg sine grating stimulus was used to measure the binocular- and monocular (dominant eye) RTs of each subject at 64 different contrast levels (from 100% to two times threshold). The results have been used to calculate a linear RT vs. 1/contrast function.

Binocular RTs have been lower than monocular for all levels of defocus and all subjects. They reached the same RT values as monocular at about 0.75 dpt higher defocus, indicating a binocular advantage in defocus tolerance of 0.75 dpt.

Combining the defocus-RT data with the contrast-RT data allowed a conversion of reaction time to perceived contrast. Perceived contrast was significantly higher for binocular compared to monocular viewing. The binocular increase of perceived contrast was calculated and an average binocular summation factor of 2.43 was found. There was no correlation between binocular summation and amount of defocus.

Monocular and Binocular depth of focus has been calculated, using the defocus-RT data and individually defined RTs as blur criteria. Depth of focus was found to be constantly higher for binocular viewing. The magnitude of increase showed a high inter-subject variance and was in the range from 0.18dpt to 0.92dpt. Possible reasons for these results have been discussed.

Additionally it was possible to compare the results of above described experiment for horizontally and vertically oriented sine gratings. It turned out, that binocular reaction times for vertical gratings are slightly lower until 1.5dpt defocus, but higher for defocus levels above this. It was found that the insufficient spatial overlap of the binocular images caused an effective contrast loss for vertical, compared to horizontal gratings.

At last, negative defocus and the accommodative range has been briefly investigated. Accommodative range found to be much higher for monocular viewing than for binocular. Reason for this discrepancy is the vergence movement of the eyes during accommodation which causes effective diplopia for the 3m distant stimulus.

The measurement of simple visual reaction times found to be a reliable and precise psychophysical /behavioral method to assess several aspects of visual performance.

Περίληψη

Στην παρούσα μελέτη, πραγματοποιήθηκαν μετρήσεις απλών χρόνων αντίδρασης και έγινε ανάλυση και αξιολόγηση της επίδρασης σε αυτούς, τόσο της αντίθεσης όσο και της απεστίασης. Όλες οι μετρήσεις έγιναν μονόφθαλμα και διόφθαλμα.

Πραγματοποιήθηκαν μετρήσεις των χρόνων αντίδρασης διόφθαλμα και μονόφθαλμα (στον οδηγό οφθαλμό) σε έξι συμμετέχοντες (ηλικία: 25-40 έτη), για διαφορετικά επίπεδα απεστίασης με θετικούς φακούς (έως 4.25 διοπτρίες) . Χρησιμοποιήθηκε ερέθισμα ημιτονοειδούς διαμόρφωσης (grating) με αντίθεση 10%, και χωρική συχνότητα 4c/deg. Επίσης , χρησιμοποιώντας το ίδιο ερέθισμα, μετρήθηκαν οι χρόνοι αντίδρασης για 64 διαφορετικά επίπεδα φωτεινής αντίθεσης(από 100% έως το διπλάσιο της ουδού (threshold)). Τα αποτελέσματα χρησιμοποιήθηκαν για τον υπολογισμό της συνάρτησης μεταξύ των χρόνων αντίδρασης και του 1/contrast function.

Οι χρόνοι αντίδρασης διόφθαλμα ήταν χαμηλότεροι από ότι για τον έναν οφθαλμό για όλα τα επίπεδα απεστίασης και για όλους τους συμμετέχοντες. Οι χρόνοι αντίδρασης διόφθαλμα έφθασαν τα ίδια επίπεδα με τους χρόνους αντίδρασης μονόφθαλμα για απεστίαση κατά 0.75 Διοπτρίες υψηλότερη από αυτή για μονόφθαλμα, καταδεικνύοντας ένα πλεονέκτημα διόφθαλμα σχετικά με την ανοχή στην απεστίαση κατά 0.75 Διοπτρίες.

Συνδυάζοντας τα δεδομένα από τους χρόνους αντίδρασης για διαφορετικούς βαθμούς απεστίασης , με αυτά των χρόνων αντίδρασης για διαφορετικά επίπεδα ευαισθησίας αντίθεσης, κατέστη δυνατό να γίνει μετατροπή των χρόνων αντίδρασης σε αντιλαμβανόμενη ευαισθησία αντίθεσης (perceived contrast). Η Perceived contrast ήταν μεγαλύτερη για την διόφθαλμη σε σχέση με την μονόφθαλμη όραση. Έγινε υπολογισμός της αύξησης του perceived contrast διόφθαλμα και στην συνέχεια υπολογίστηκε η μέση τιμή της διόφθαλμης συνεργικής δράσης (binocular summation) και βρέθηκε 2.43. Δεν βρέθηκε καμία συσχέτιση μεταξύ binocular summation και βαθμού απεστίασης.

Στην συνέχεια έγινε υπολογισμός του βάθους εστίασης μονόφθαλμα και διόφθαλμα, αφού έγινε προσδιορισμός του ατομικού κριτηρίου «θολής εικόνας» (blur criteria), σε συνδυασμό με τις μετρήσεις από τους χρόνους αντίδρασης σε σχέση με την απεστίαση, για κάθε εξεταζόμενο ξεχωριστά. Το βάθος εστίασης βρέθηκε να είναι σταθερά υψηλότερο για την διόφθαλμη όραση. Το μέγεθος της αύξησης έδειξε μία μεγάλη διακύμανση μεταξύ των διαφορετικών εξεταζόμενων με εύρος από 0.18 έως 0.92 Διοπτρίες. Οι πιθανοί λόγοι για αυτά τα ευρήματα συζητήθηκαν εκτενώς.

Επιπρόσθετα, έγινε σύγκριση των αποτελεσμάτων του παραπάνω πειράματος για μετρήσεις με χρήση οριζόντιας και κάθετης κατεύθυνσης ημιτονοειδών διαμορφώσεων (gratings). Τα αποτελέσματα αυτής της σύγκρισης έδειξαν ότι οι χρόνοι αντίδρασης διόφθαλμα για ερεθίσματα κάθετης διαμόρφωσης είναι ελαφρώς χαμηλότεροι έως και την τιμή απεστίασης ίση με 1.5 Διοπτρίες, αλλά είναι μεγαλύτεροι για επίπεδα απεστίασης μεγαλύτερα από 1.5 Διοπτρίες. Βρέθηκε ότι η ελλιπής χωρική αλληλοεπικάλυψη των εικόνων διόφθαλμα, ήταν η αιτία για την συμπτωματική απώλεια αντίθεσης στην περίπτωση των ερεθισμάτων κάθετης κατεύθυνσης σε σύγκριση με αυτά οριζόντιας κατεύθυνσης.

Στο τέλος πραγματοποιήθηκε και μία συνοπτική διερεύνηση του εύρους προσαρμογής καθώς και της απεστίασης με αρνητικούς φακούς. Το εύρος προσαρμογής βρέθηκε να είναι πολύ μεγαλύτερο στην μονόφθαλμη από ότι στην διόφθαλμη όραση. Πιθανό λόγο για αυτό το εύρημα μπορεί να αποτελεί η σύγκλιση των οφθαλμών κατά την διάρκεια της προσαρμογής, η οποία και προκαλεί διπλωπία για ένα ερέθισμα που βρίσκεται σε απόσταση 3μ.

Η μέτρηση των απλών χρόνων αντίδρασης βρέθηκε να είναι ακριβής και αξιόπιστη ψυχοφυσική μέθοδος για να αξιολογηθούν και να μελετηθούν διαφορετικές διαστάσεις της απόδοσης της όρασης.

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1. Introduction

1.1 The human visual pathway

The perception of light is the most important sense for a human. A big part of our neural real estate is designated to the task of visual perception.

For the here presented work it is of importance to understand some of the basic features of the visual pathway. One of the fundamental findings is that the perception of visual information needs a certain time. This becomes clear when looking on the visual pathway und the complex neural mechanisms that are involved in visual perception.

When light hits the eye, the Retina with its receptor cells converts this light into a neural signal with a highly complicated neuro-chemical process. This signal is afterwards transferred by the optical nerve and the chiasm to the first relay station the Lateral Geniculate Nucleus (LGN). The LGN not only relays the visual image to the visual cortex but also pre-processes the received visual information.

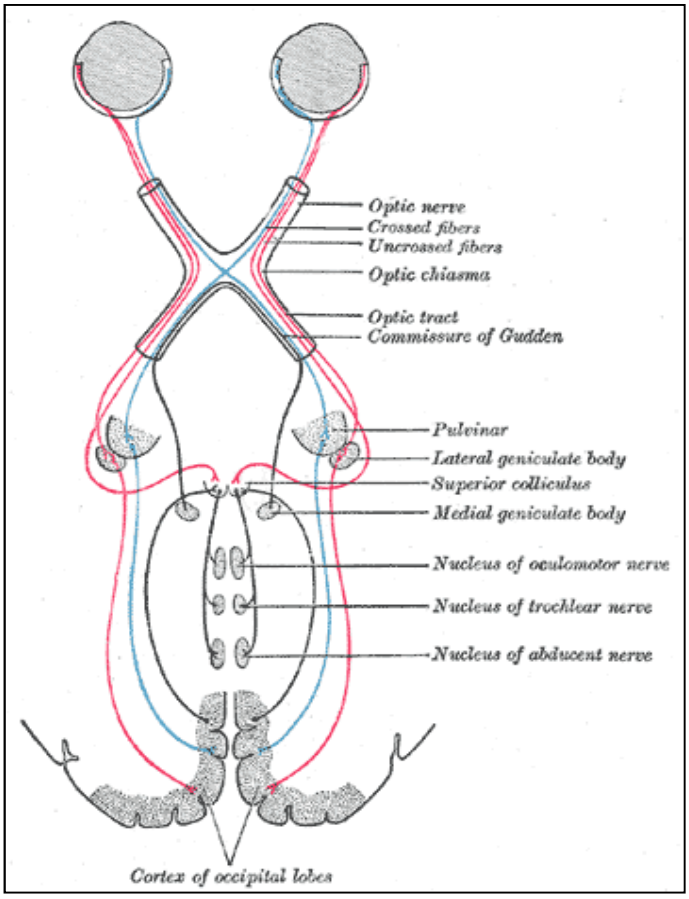

Figure 1.1.1: Schematic of the human visual pathway (Image courtesy: Wikipedia)

The primary visual cortex (V1) receives visual signals directly from the LGN and visual information then flows through a cortical hierarchy. Every cortical level is responsible for a certain type of perception task and typically these

tasks get more sophisticated as the level is rising (up to V5).

For the understanding of certain phenomena connected with visual reaction time experiments one feature of the visual pathway is of special importance. It is the division of the visual pathway in two distinctive channels, the Magno- (or transient) and Parvo- (or sustained channel). Figure 1.1.2 illustrates these two channels schematically.

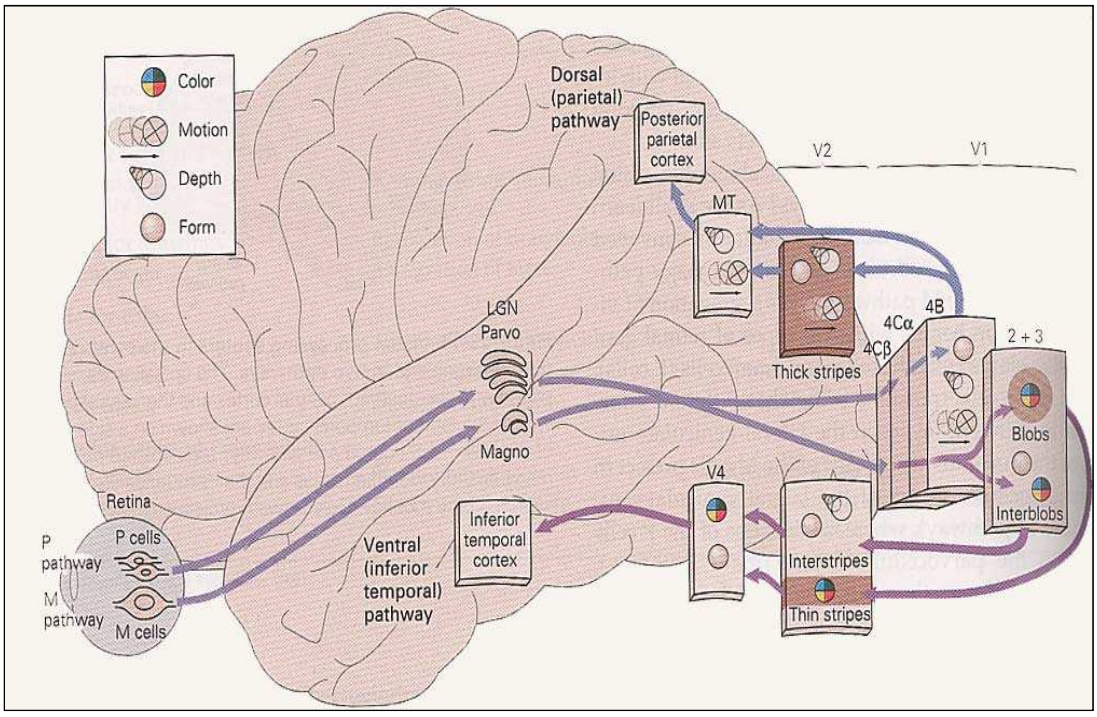

Figure 1.1.2: Magno- and Parvo-pathway

Each channel contains a certain population of cells and connects specific areas of LGN and visual cortex. Important for our experiments is the fact that each channel responds differently to visual stimuli. Table 1.1.1 summarizes the significant properties of each channel.

	Magno/transient	Parvo/sustained
Speed	Fast	Slow
Spatial resolution	Low	High

Contrast Sensitivity	High	Low
Colour Sensitivity	No	Yes

Table 1.1.1: Properties of Magno- and Parvo-channel

Two properties have to be specially mentioned. One is the difference in contrast sensitivity and the other the differences in spatial resolution. Stimuli containing only high spatial frequencies stimulate exclusively the Parvo-channel, while low contrast stimuli stimulate exclusively the Magno-channel.

1.2 Visual reaction times

As described in the previous chapter visual perception is a complex process and some time is needed from the moment when light enters the eye to the moment when this light is perceived. This time is called perception time (PT) and is a part of the overall visual reaction time.

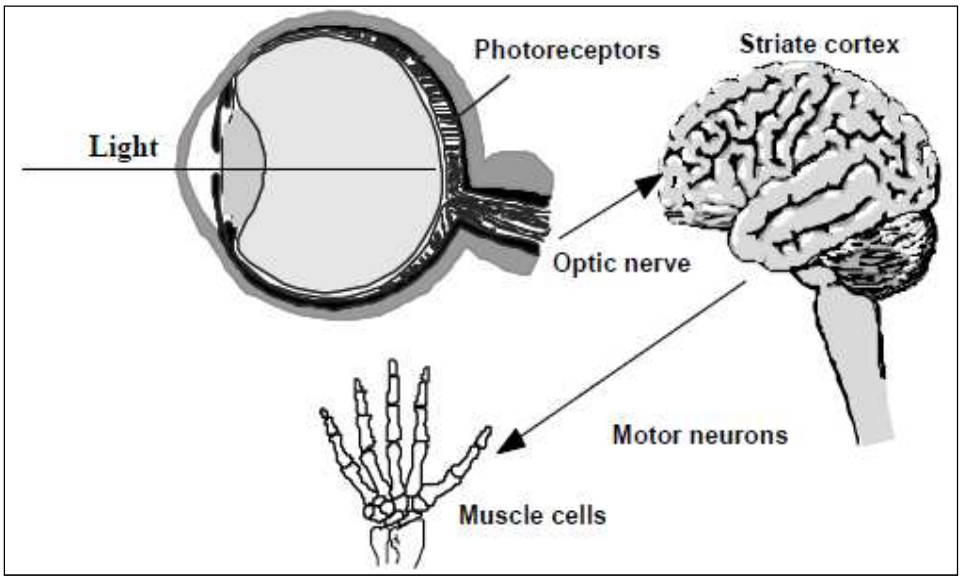

Figure 1.2.1: Schematic way of signal at visual reaction

There are 3 different types of visual reaction times:

- Simple reaction time
- Recognition reaction time
- Choice reaction time

Simple reaction time is defined as:
"The interval between the onset of a stimulus and the response under the condition that the subject is instructed to respond as rapidly as possible" (Teichner 1954)
In contrast to recognition or choice tasks the subject has to make no decision about the quality of the stimulus.
Recognition reaction time is the reaction time to a set of stimuli, where the subject has to decide if the stimulus is right or wrong (e.g. In a set of colored stimuli, the subject is instructed to respond only to green stimuli.). These reaction times are generally higher that simple reaction times.
The longest reaction time is needed for choice tasks, where the subject responds differently to respective stimuli. (e.g. When a certain letter appears on a screen the subject has to press the correct key on a keyboard)

In our experiments we will use only simple visual reaction time. No recognition or choice task is involved. The simple visual reaction time (RT) consists of mainly two parts, the perception time (PT) as described above and the motor time (MT). Motor time is the time from when the stimulus is perceived until the responding organ triggers a "stop" signal (e.g. thumb presses a button).

$$RT=PT+MT \qquad [1.2.1]$$

While the Motor time is nearly constant for one subject, the perception time is highly influenced by the quality of the visual stimulus. Several stimulus parameters influence the perception time and details are displayed in table 1.2.1

Stimulus parameter	Shorter RT when parameter is:	Comments
Contrast	High	Small RT changes at high contrasts
Luminance	High	RT improves until a certain saturation level
Duration	High	Small change when T>10ms
Spatial frequency	Low	Contrast dependent
Retinal position	High L: center Low L: periphery	Luminance (L) depended
Color	Green/red	RTs for green/red are faster than for blue/yellow stimuli

Table 1.2.1: Visual stimulus parameters and their influence on RT

Several other factors can influence the reaction time as a whole. These include tiredness, age, stress, drugs, distraction and others. When performing RT experiments, these factors should be taken into account.

The relation between contrast and simple visual reaction time has been investigated in the past. Two findings are of special importance for our experiments. One is the biphasic behaviour of reaction times vs. contrast functions (Harwerth and Levi 1978) and the other the linearity of RT vs. 1/contrast (Plainis and Murray 2000).
As explained in section 1.1 there are 2 different visual channels (Mango and Parvo) with different properties. Reaction time experiments can show, that these differences between the channels can cause a biphasic contrast-RT function.

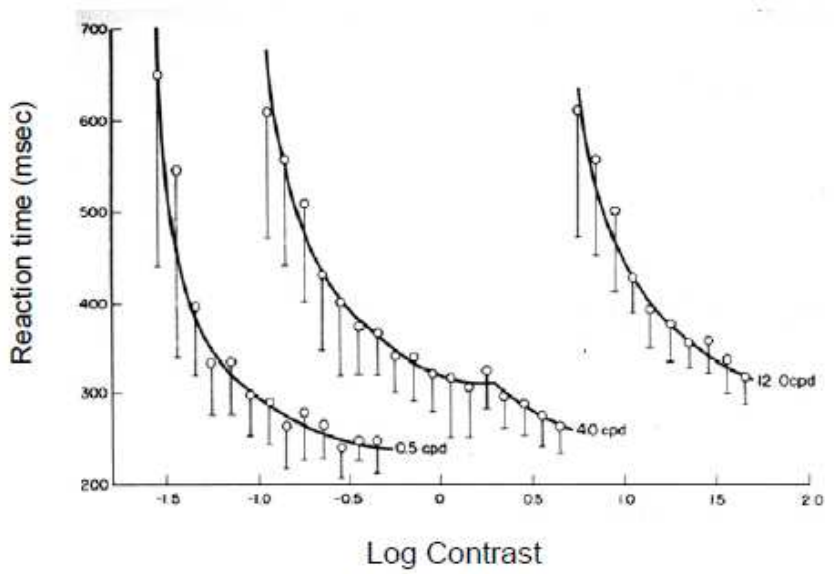

Figure 1.2.2: Simple visual reaction times vs. contrast for three different spatial frequencies (0.5, 4.0 and 12 c/deg). The curve for the 0.5 c/deg stimulus is on a true scale, but the other curves have been successively shifted to the right by 1 log unit for ease of viewing. (from (Harwerth and Levi 1978))

The graph for 4.0 c/deg in figure 1.2.2 illustrates this biphasic behaviour. At high contrasts, the Parvo channel dominates the RTs, while at lower contrasts the Magno channel dominates. The left graph for 0.5 c/deg is based completely on Magno response, while the high spatial frequency of the right one (12c/deg) allows only Parvo response.

If a contrast vs. RT graph is converted to a 1/contrast vs. RT graph one can observe a nearly perfect linear fit of the data. This finding was pointed out by (Plainis and Murray 2000) and the following contrast-RT function was proposed:

$$T = T_i + b(1/C) \qquad [1.2.2]$$

With: T = Reaction Time

T_i = Reaction time at full contrast (function intercept)

b = Slope

C = Contrast

The variables k and RT_0 are strongly influenced by the stimulus spatial frequency and show a significant variation between subjects. However, they can be determined for a certain spatial frequency on one subject and the so created function can be used to convert measured reaction times to perceived contrast. The slope k is a measure of contrast sensitivity, as smaller (and flatter the graph) as higher the contrast sensitivity for that spatial frequency (or subject). Figure 1.2.3 illustrates the variation in k.

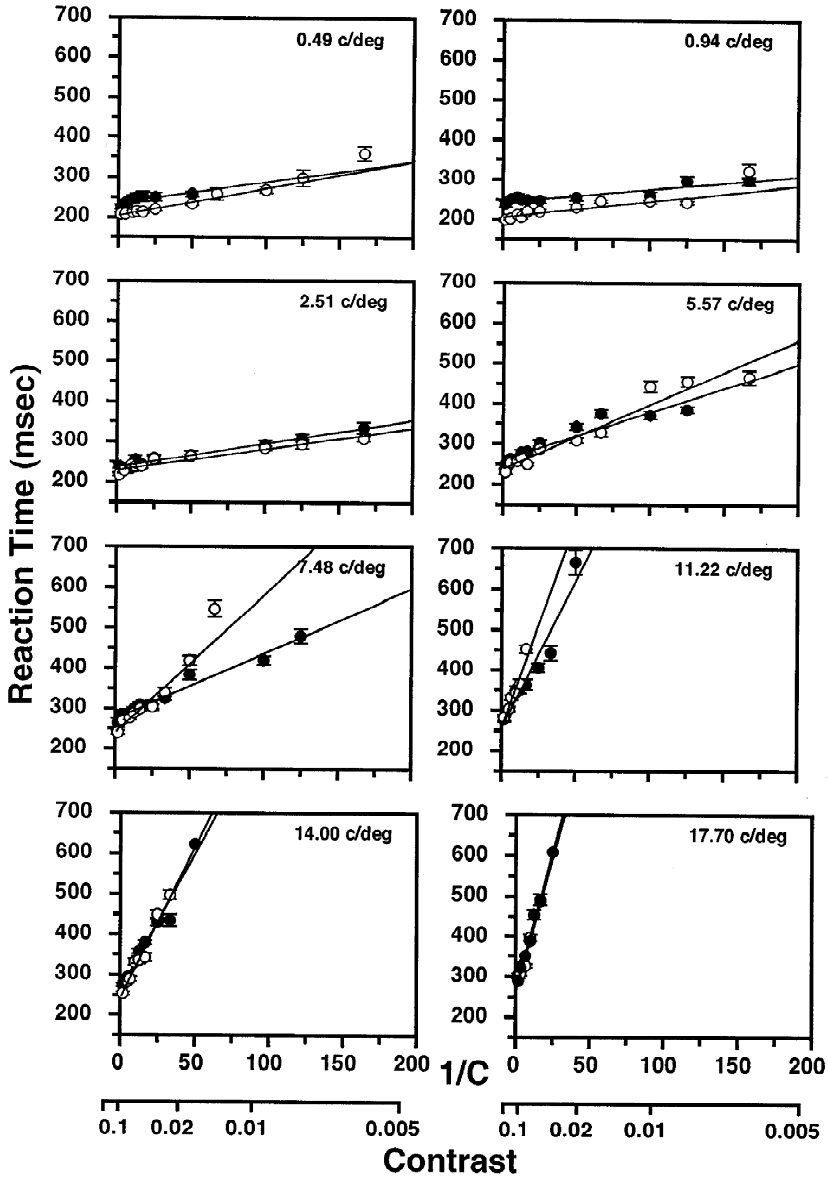

Figure 1.2.3: RT vs. 1/C graphs of two subjects for different spatial frequencies (from (Plainis and Murray 2000))

1.3 Defocus and Depth of focus

Defocus decreases the contrast of a sine grating and reduces its detectability. Higher spatial frequencies show a significant decrease of contrast; while for spatial frequencies below 2

c/deg it remains nearly unaffected in terms of detectability. This effect of defocus on the contrast sensitivity function (CSF) is well documented (Campbell and Green 1965).

However, blurring a sine grating by defocus does not cause a monotonous decrease in contrast as it would be expected. When a sine grating is defocused the contrast drops nearly to zero as defocus is rising, but when increasing defocus further, contrast is rising again (Hopkins 1955). This phenomenon is called spurious resolution and it is caused by the increase of PSF and the subsequent overlap of neighboring maxima (Smith 1982). It can be observed when looking at different spatial frequencies for a certain defocus, as shown in figure 1.3.3. But the same effect appears when looking at different levels of defocus for a fixed spatial frequency grating. Using the simulation of a model eye, the contrast transfer function was calculated for a 4c/deg sine grating at different levels of defocus. Figure 1.3.1 shows the resulting graphs.

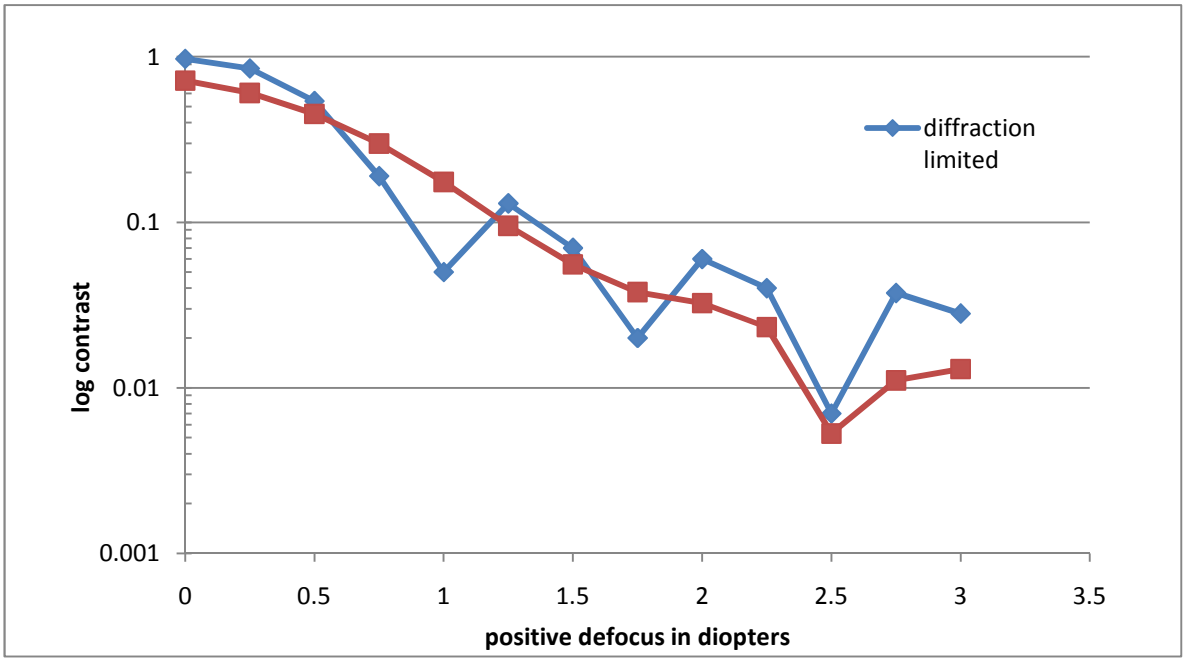

Figure 1.3.1: Simulated contrast transfer function of a diffraction limite (blue) and aberrated (red) model eye for a 4c/deg sine grating at different levels of defocus. (courtesy: A.Pallikaris)

The graphs in figure 1.3.1 illustrate not only the strong effect of spurious resolution for a diffraction limited model eye, but also the significant difference when the same calculation is

made for an aberrated model eye. Obviously high order aberrations can decrease the effect of spurious resolution and smoothen the transfer function graph (Walsh and Charman 1989).

Understanding spurious resolution is of high importance when performing psychophysical defocus experiments with gratings.

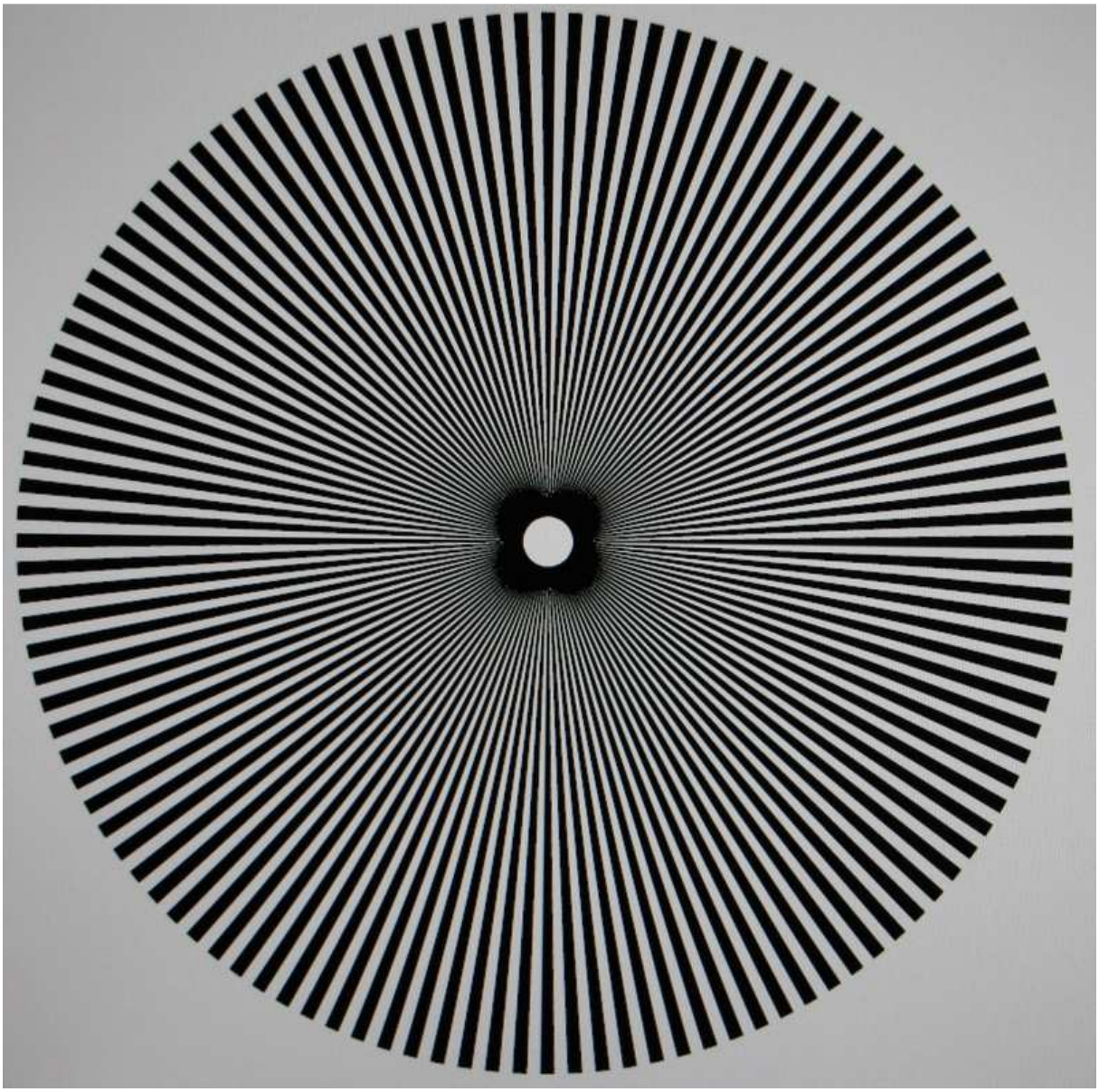

Figure 1.3.2: Star segment target with different spatial frequencies photographed from a LCD monitor in focus.

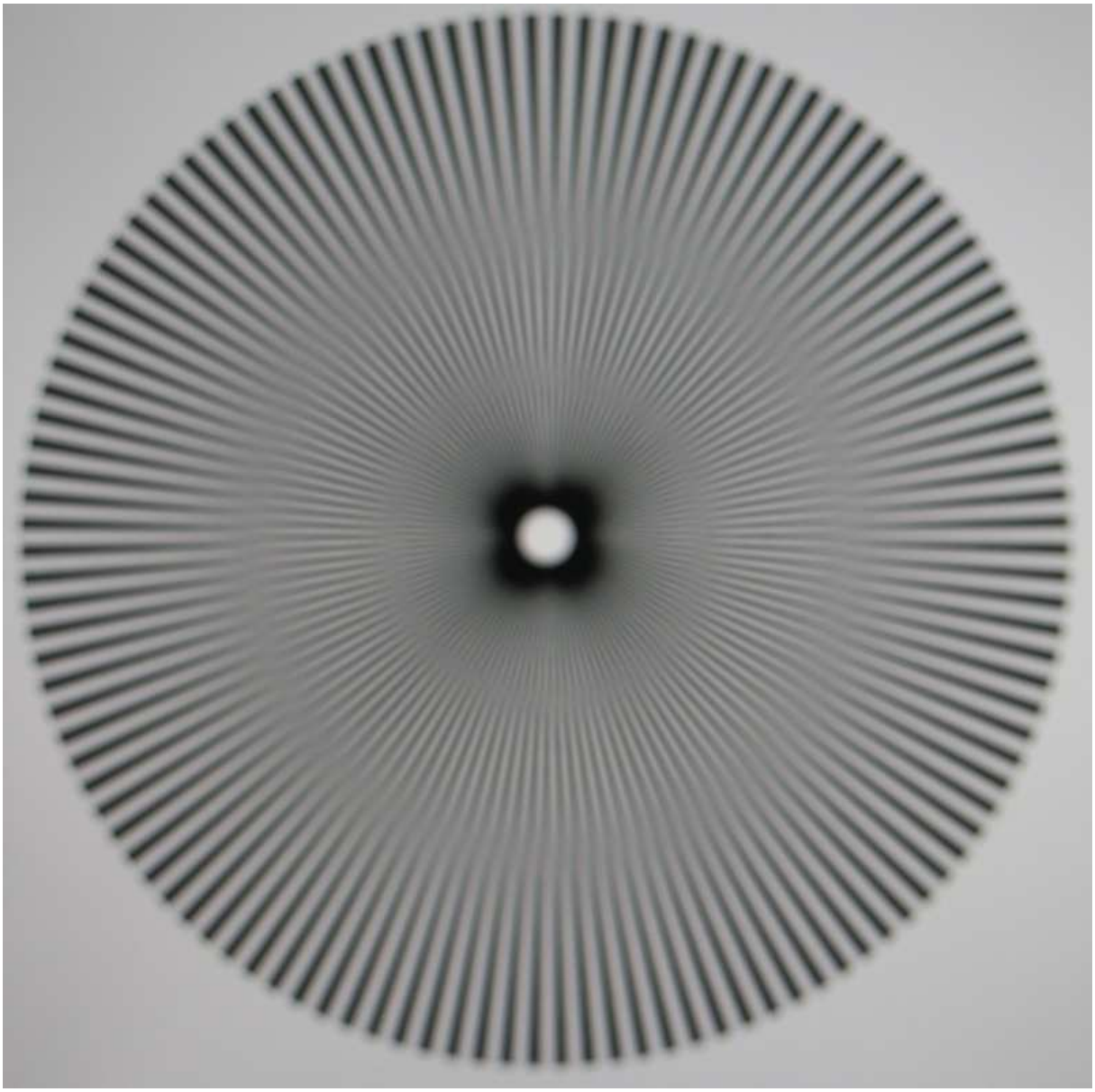

Figure 1.3.3: The same star segment target from figure 1.3.1 photographed from a LCD monitor and purposely defocused. Note the ring-shaped areas of minimal contrast (nodal points) , spurious resolution and contrast reversal. (after (Smith 1982))

From geometric optics we know that a lens has a focal length and images an object exactly at its focal plane. If we are moving the object axially, the focal plane moves as well. But when we have a fixed lens to image plane distance (e.g. a camera) the image will get blurred as more the object moves away from its conjugate focal point. So, depth of focus is the axial distance of both sides of the focal image plane where the image appears acceptably sharp. The acceptable sharpness is defined by the allowable blur circle (see figue1.3.4). Depth of focus in image space is virtually the same as depth of

field in object space. The ratio between them is defined by the focal length of the lens and the object distance.

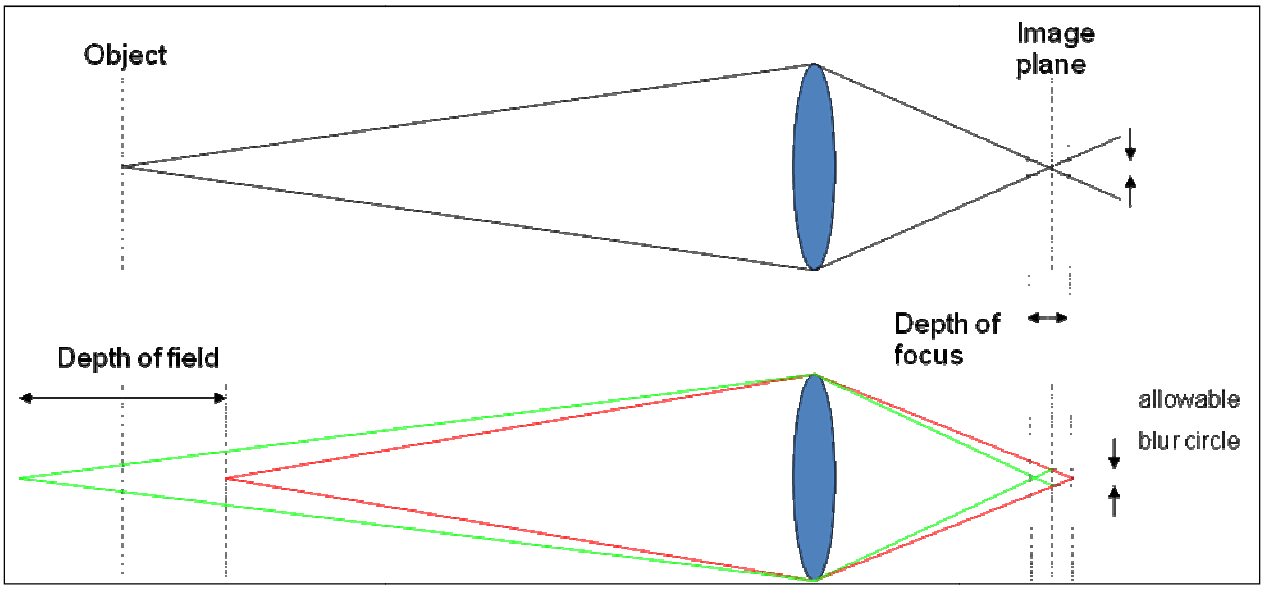

Figure 1.3.4: Depth of field and depth of focus

As one can see the depth of focus relies very much on the acceptance criteria, the allowable blur circle. This means that the sensor that detects the image is of biggest importance when defining the depth of focus. If we take a CCD camera as image sensor, we could say that our allowable blur circle may be as big as the size of one pixel. That guarantees that the output image will be exactly the same as if it would be in exact focus.

Looking at the eye, we get a similar situation like in a camera with a fixed lens to image plane distance (see figure 1.3.5). Changes in object distance in a physiological eye would cause an accommodative response and shift the image plane. It is important to understand that this accommodative range has nothing to do with depth of focus. Depth of focus is determined when the eye is not accommodating (cycloplegia, pseudophakic). The allowable blur circle criterion for the eye can be defined by the perceptive tolerance of blur. This blur threshold is very different for each eye and can therefore lead to very different depth of focus in the population.

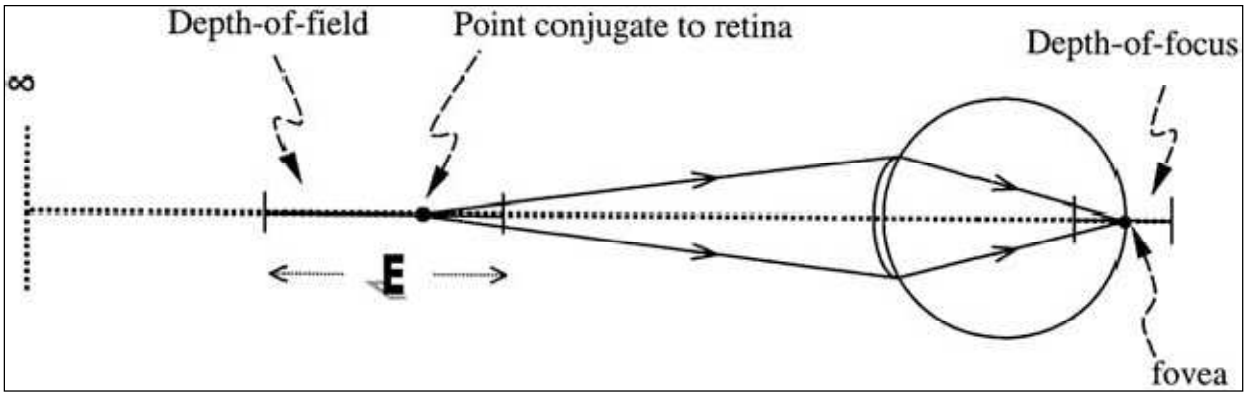

Figure 1.3.5: Depth of focus in the eye (from (Wang and Ciuffreda 2006))

The biggest impact on depth of focus has certainly the pupil size. Figure 1.3.6 shows the effect of pupil size change on the size of the blur circle. The decrease of pupil size increases the depth of focus. For pupils above 4mm the effect gets smaller due to the influence of aberrations. The increase of depth of focus due to higher aberrations for big pupils compensate for their decrease of depth of focus.

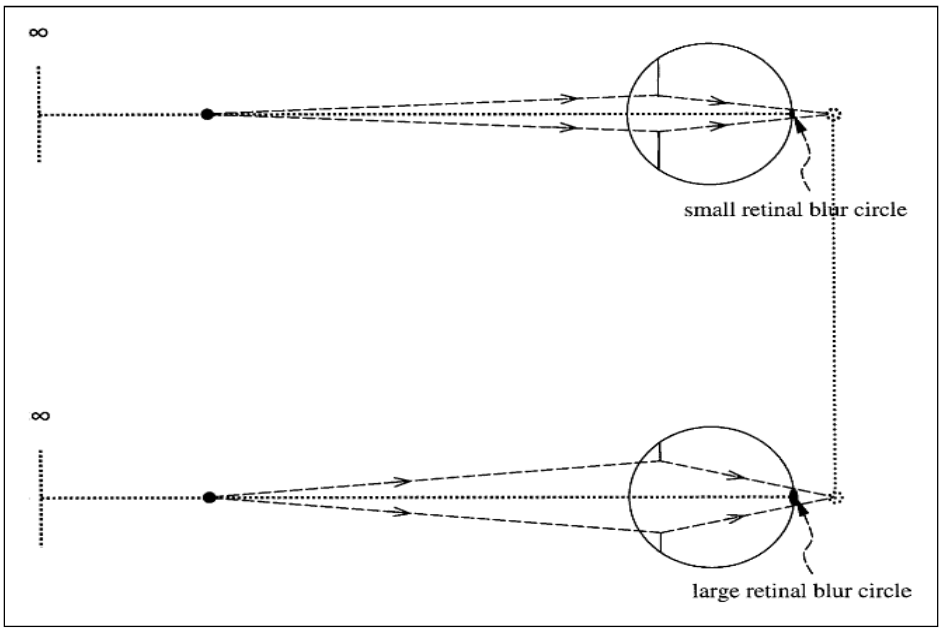

Figure 1.3.6 Pupil size and blur circle size (from (Wang and Ciuffreda 2006))

Factors that deteriorate the image quality in foveal focus have always an influence on the depth of focus. If these factors increase, the depth of focus typically increases as well.

One of these factors is the low- and high order aberrations of the eye (Rocha, Vabre et al. 2009). Low order aberrations like defocus and astigmatism as well as high order aberrations (especially spherical aberration) are increasing the depth of focus.

When measuring depth of focus, the appearance of the target/object is of great importance. Luminance, contrast and spatial frequency are directly related to the blur threshold and therefore with the measured depth of focus. Increasing each of these parameters decreases the depth of focus, because blur is perceived earlier.

1.4 Binocular summation

Apart from Stereopsis and larger optical field there is a benefit of binocularity, which improves visual performance beyond what would be expected from one eye. This effect is called binocular summation and is usually investigated using threshold methods. Several publications show, that binocularity improves the visual perception significantly by a factor of 1.1 to more than 3, depending on the type of visual parameter investigated.

Binocular improvement of 11% for supra-threshold visual acuity measurements has been reported (Cagenello, Arditi et al. 1993), while Campbell and Green (Campbell and Green 1965) found a binocular summation factor of 1.4 for contrast sensitivity at near threshold stimuli. Visual evoked potentials at +2D defocus increase binocularly by more than 300% (Plainis, Petratou et al.) compared to abut 60% in best focus. Similar high summation factors have been reported for electrophysiological experiments in animals.

There are a few theories what is the reason for that improvement and the simplest one is based on probability summation. It just says that 2 detectors have an up to sqrt2 higher probability to detect a stimulus than one alone. This is valid only for near-threshold stimuli, where each detector has a certain probability well below 1.0 to detect the stimulus.

At supra-threshold stimuli, the probability to detect a stimulus is nearly 1.0 for each eye and so the probabilistic approach cannot be applied. However, certain experiments like reaction

time measurements allow a probabilistic improvement, even for supra-threshold stimuli. Reaction time measurements to a certain stimulus show always some deviation for each eye. Assuming now, that a binocular reaction time is always the smaller of the two hypothetic monocular reaction times allows a small probabilistic improvement (Westendorf and Blake 1988).

Several experiments have shown that there is a stronger improvement of certain visual parameters under binocularity, which cannot be explained by probability summation alone. Matin (Matin 1962) and others proposed a neural summation - the input from both eyes are added and generate a stronger neural response which leads to a better visual perception. In order for this binocular summation to take place, stimuli have to be spatially and temporally overlapping. Binocular summation cannot be observed if different retinal areas are stimulated, or if the stimuli have a certain time offset.

Campbell and Green (Campbell and Green 1965) provide another possible explanation which is based on an improved signal to noise ratio. Since every neural signal contains noise, the intensity of a stimulus must be above the noise level in order to be detected. Adding two neural signals of the same stimulus can increase the signal to noise ratio because the signal is doubled while the random noise is partly canceled.

2 Methodology

2.1 Subjects

Six volunteers (1 female, 5 males) with an average age of 31.8 years (range: 25 to 40 years) participated in the study. All subjects had a spectacle-corrected decimal visual acuity ≥ 1.0 in each eye, normal binocular vision, phoria and near point of convergence, and no ocular pathology. All volunteers had ≤ 2.0D of spherical refractive error and ≤ 0.50D of astigmatism. None of the participants had a history of refractive or other ocular surgery. Verbal consent was obtained from all participants after they had received an oral explanation of the nature of the study. The study was conducted in adherence to the tenets of the Declaration of Helsinki and followed a protocol approved by the University Research Board.

2.2 Materials

Measurements took place in low photopic lighting conditions, in a sound-attenuated room. The stimulus was displayed on a Sony GDM F-520 CRT monitor by means of a VSG 2/5 stimulus generator card (Cambridge Research Systems Ltd, UK).

Mean screen luminance was 30 cd/m^2 and the gamma functions of the red, green and blue guns of the monitor were calibrated with a PR-650 spectro-radiometer (Photoresearch, Chatsworth, CA).

Stimulus was a circular field with a 4 c/deg monochromatic sinusoidal vertical or horizontal grating. The total field diameter was 5deg with a central 3deg homogeneous 10% contrast area and a Gaussian transition annulus to 0% contrast. In all conditions the test grating was modulated within a square wave temporal window of 380 ms duration. Contrast was defined in terms of Michelson, i.e. L_{max}-L_{min}\L_{max}+L_{min}. The stimulus area was surrounded by a neutral

background (chromatic coordinates x=0.310, y=0.316) of the same luminance. Fixation was achieved using a centrally projected black cross.

The stimulus parameters have been set using the "NewRT" software Version196 from Neil Perry. The same software has been used for data acquisition.

RTs were measured using an IR remote trigger (Cambridge Research Systems Control Box CB6) and an IR Receiver (Cambridge Research Systems) connected to a Personal Computer.

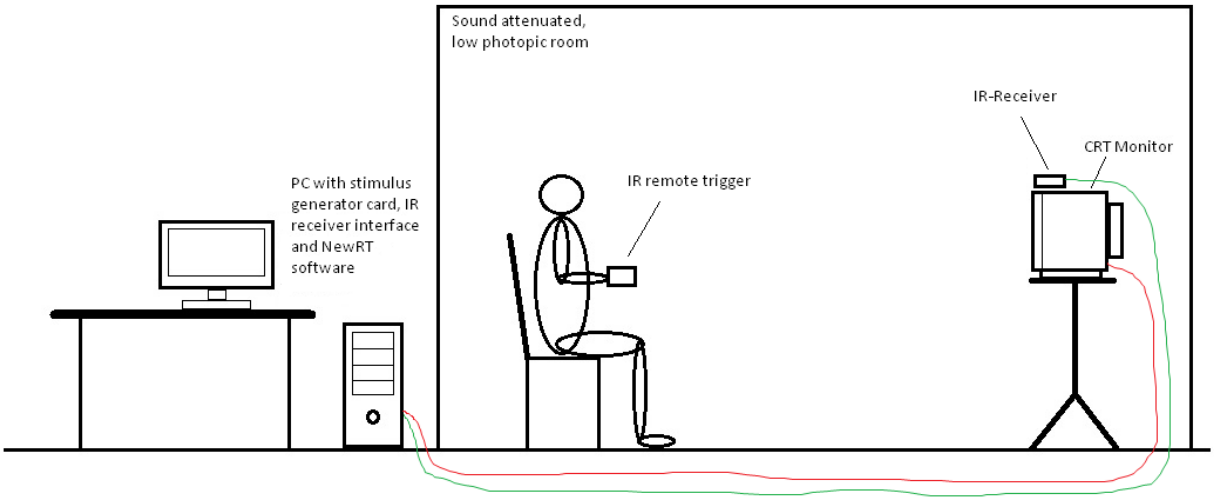

Figure 2.2.1: Schematic of experimental set up.

2.3 Procedures

All measurements were performed at 3m distance between eye and Monitor, monocularly (with the dominant eye) and binocularly, with best spectacle correction and natural pupils. Eye dominancy was defined by looking through a central hole in an A4 card, held by the participant in both hands away from the body. During the monocular measurements the non-dominant eye was covered with an eye patch.

The order of viewing testing (monocular vs. binocular) was counter-balanced.

2.3.1 Determination of contrast threshold using Method of adjustment

At start the stimulus was displayed with 100% contrast.

The subject could increase or decrease the stimulus contrast by pressing the corresponding buttons at the control box. One press of a button changed the contrast by 1 dB. When the subject could just perceive the stimulus it was instructed to press a confirmation button and the contrast level was recorded by the software. This procedure was performed 5 times and the 5 contrast levels have been averaged. This averaged value was taken as the subjects perception limit in dB.

2.3.2 Simple reaction times at different levels of contrast (Contrast-RT function)

Each subject was instructed to press the trigger button with its left thumb as fast as possible when the stimulus appears.

The first stimulus was displayed with a contrast of 100%. Each of the following of totally 64 stimuli was displayed with smaller contrast then the previous until the last stimulus was displayed with a contrast of two times the perception limit (which was determined before). The contrast difference (step) between two following stimuli was always the same. When a stimulus was recognized (button pressed) the software displayed the next stimulus after a random time between 1s and 3s. No response for 5s after stimulus display was considered a timeout and the next stimulus was displayed.

These measurements were filtered for outliers. In a first step RT measurements have been defined as outliers when their values have been below 200ms or above 500ms. Linear regression was applied to the remaining valid values. All values above or below one standard error of the linear regression were excluded as well.

2.3.3 Simple reaction times at different levels of positive defocus

Each subject was instructed to press the trigger button with its left thumb as fast as possible when the stimulus appears.

45 single measurements were obtained for each defocus condition. When a stimulus was recognized (button pressed) the software displayed the next stimulus after a random time between 1s and 3s. No response for 5s after stimulus display was considered a timeout and the next stimulus was displayed.

These measurements were filtered for outliers and afterwards averaged. Measurements were considered invalid, when the RT was above 700ms or below 200ms. Standard deviation (SD) and Median (M) was calculated for the remaining valid data and it was filtered in a second step were all values higher M+1.5*SD or lower M-1.5*SD were excluded.

Defocus was induced and stepwise increased by using positive spherical powered lenses on a trial frame at 12mm Vertex distance. The first measurement series was done always without defocus and the second with +0.50 D of defocus. The defocus was afterwards increased for each measurement by +0.25 D steps until the individual perception limit was reached. This limit was defined as the amount of defocus where less than 23 of the 45 single RT measurements were valid.

The effective defocus was calculated out of applied defocus and Vertex distance for each subject and condition. The difference between effective and applied defocus for the positive defocus experiments was at maximum 0.08dpt (subject AL at +2.25dpt defocus), but mostly below 0.05dpt. It was decided that no correction will be applied for this, as the difference is negligible.

3 Results

3.1 Contrast-RT function

Simple reaction times vs. Contrast (Michelson) have been determined for each subject and condition individually.

Because this data shows a significant scatter, the measurements have been filtered to exclude outliers. At first all RT above 500ms and below 200ms have been excluded. The remaining RT data have been used to create a first linear regression line plotted against 1/Contrast. In the next step every RT value exceeding the predicted value from this first linear regression by ±1.5 x Standard error was excluded as well.

Finally a linear regression of the remaining RT data vs. 1/C has been calculated.

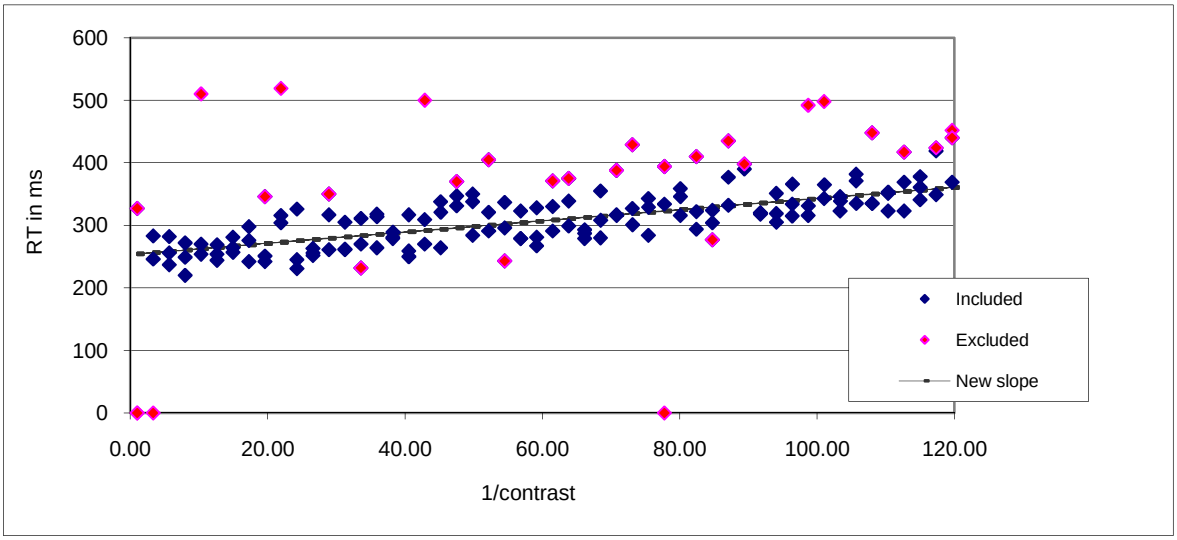

Figure 3.1.1: Example of a RT vs 1/C plot for subject BA (Binocular, vertical grating)

The slope and intercept data have been extracted and define the individual Contrast-RT function for each subject and condition:

$$T = b \times 1/C + T_i \qquad [3.1]$$

With: T = reaction time

b = slope

C = Michelson Contrast

T_i = Intercept (T at highest C)

The values of T_0 have been normalized to match the more accurate, separately measured reaction times at 10% contrast (see 3.2).

B $_{bino}$

Subject	Slope b monocular	Intercept T_0 monocular	Slope b binocular	Intercept T_0 binocular	Ratio b_{mono}/b_{bino}
BA	1,2775	257,71	0,6541	272,08	1,95
PL	0,9163	259,23	0,4712	265,03	1,94
TO	1,2539	248,06	1,0555	249,84	1,19
AL	1,3309	279,73	0,5314	262,97	2,50
LI	0,6916	256,18	0,4673	245,29	1,48
NI	1,5902	242,13	1,0432	247,5	1,52
MEAN	**1,1767**	**257,17**	**0,7038**	**257,12**	**1,76**

Table 3.1.1: Contrast-RT function data of each subject and mean values (for vertical gratings).

Subject	Slope b monocular	Intercept T_0 monocular	Slope b binocular	Intercept T_0 binocular	Ratio b_{mono}/b_{bino}
BA	2,0172	291,27	1,5481	291,64	1,30
PL	2,6766	245,66	2,0559	227,21	1,30
TO	1,6882	270,45	1,019	268,45	1,66
AL	1,4058	264,78	0,8707	250,99	1,61

LI	1,1024	247,65	0,8902	246,12	1,24
NI	1,4894	257,6	0,9708	250,48	1,53
MEAN	**1,7299**	**262,9**	**1,2258**	**255,82**	**1,44**

Table 3.1.2: Contrast-RT function data of each subject and mean values (for horizontal gratings).

The results show a significant difference between monocular and binocular vision for each subject. With binocular vision, the slope b is comparably smaller (flatter) than with monocular Vision. Since a flatter slope means higher contrast sensitivity, Binocularity proves to be superior.

Furthermore there are big differences between subjects, especially for the slope values. This indicates a wide range of individual levels of contrast sensitivity and shows the necessity to determine these functions for each subject separately. These measurements have been used to calculate the perceived contrast for different levels of defocus (see 3.3 and 3.4).

3.2 Comparison between monocular- and binocular RT with positive defocus

For this comparison, only the measurements from horizontal gratings have been used. Vertical gratings may show artificially high reaction times at higher defocus because of missing binocular image overlap, resulting to diplopia.

Binocular reaction times have been faster than monocular for each subject and at most defocus conditions. Similar to the contrast measurements total RT values showed a significant deviation between subjects. In order to compare binocular and monocular reaction times independent from individual influence factors the values from all 6 subjects have been averaged.

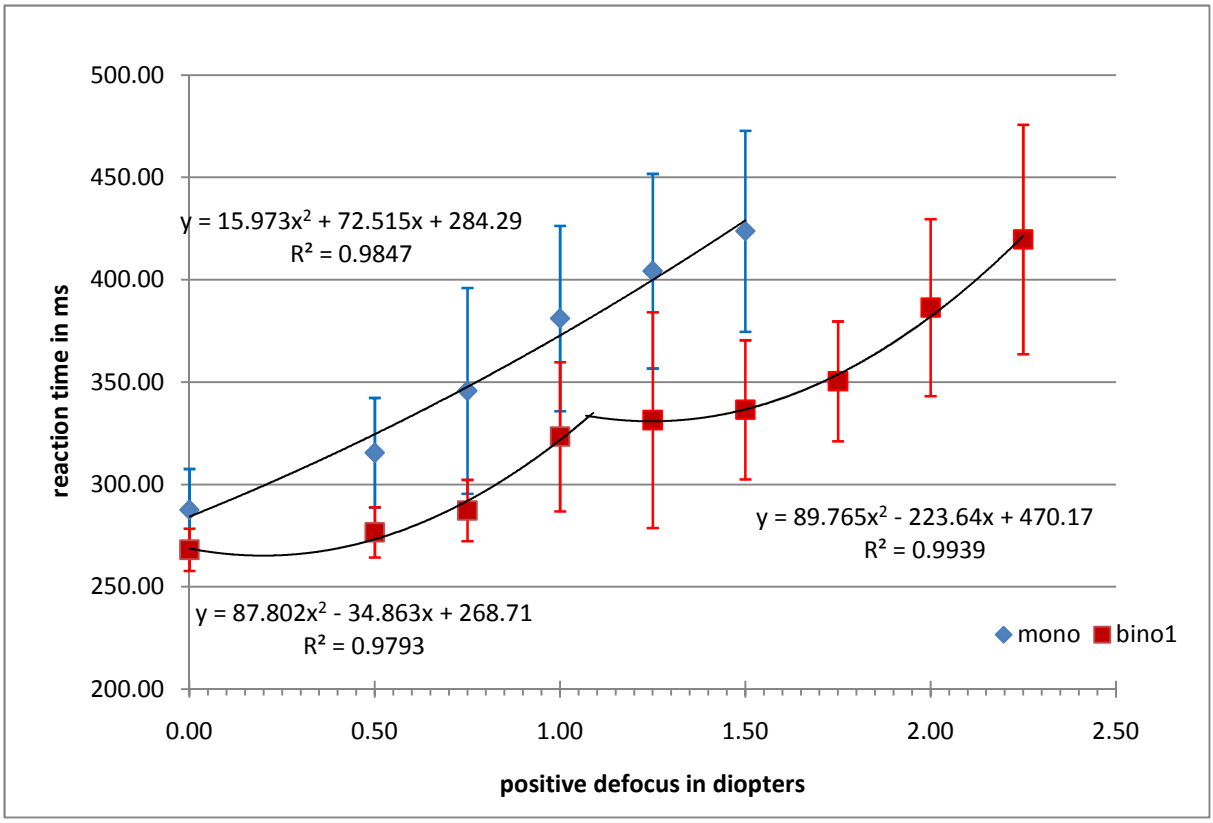

Figure 3.2.1: Averaged reaction times (horizontal gratings) from all 6 subjects as a function of defocus for binocular (red squares) and monocular (blue diamond) vision. Error bars indicate ± 1 standard deviation.

Reaction times increase nearly linear at monocular viewing, while the binocular reaction times show a kind of plateau between 1.00 dpt and 1.50 dpt of defocus. The monocular graph can be defined with a 2nd order polynomial function while the binocular looks bimodal with two 2nd order polynomials. Monocular RT for a certain defocus level is reached binocularly typically at a 0.75 dpt higher defocus. Obviously binocularity compensates for 0.75 dpt defocus compared to monocular.

Looking at the single subject's reaction times, one can see very different graphs. Especially for subjects like BA or NI, who can accept an extended range of defocus, the graphs looks much more complex and also the monocular graphs can be described only with multimodal functions.

Although the graphs between subjects look very different, there are certain similarities. Subjects BA, PL, TO and NI show a first phase of increase of RT until a defocus of approximately 1.00 dpt to 1.50 dpt for binocular and 0.75 dpt to 1.25 dpt for monocular.

After that the RT drops again to a slightly lower level and the second phase starts. This second phase can not be so well defined and shows a big variety especially for binocular. Interesting is also, that the monocular and binocular graphs look similar for one subject. The binocular graph seems to resemble the monocular, just that is shifted by 0.25 dpt to 0.50 dpt to the right, the defocus range is higher and RTs are generally faster

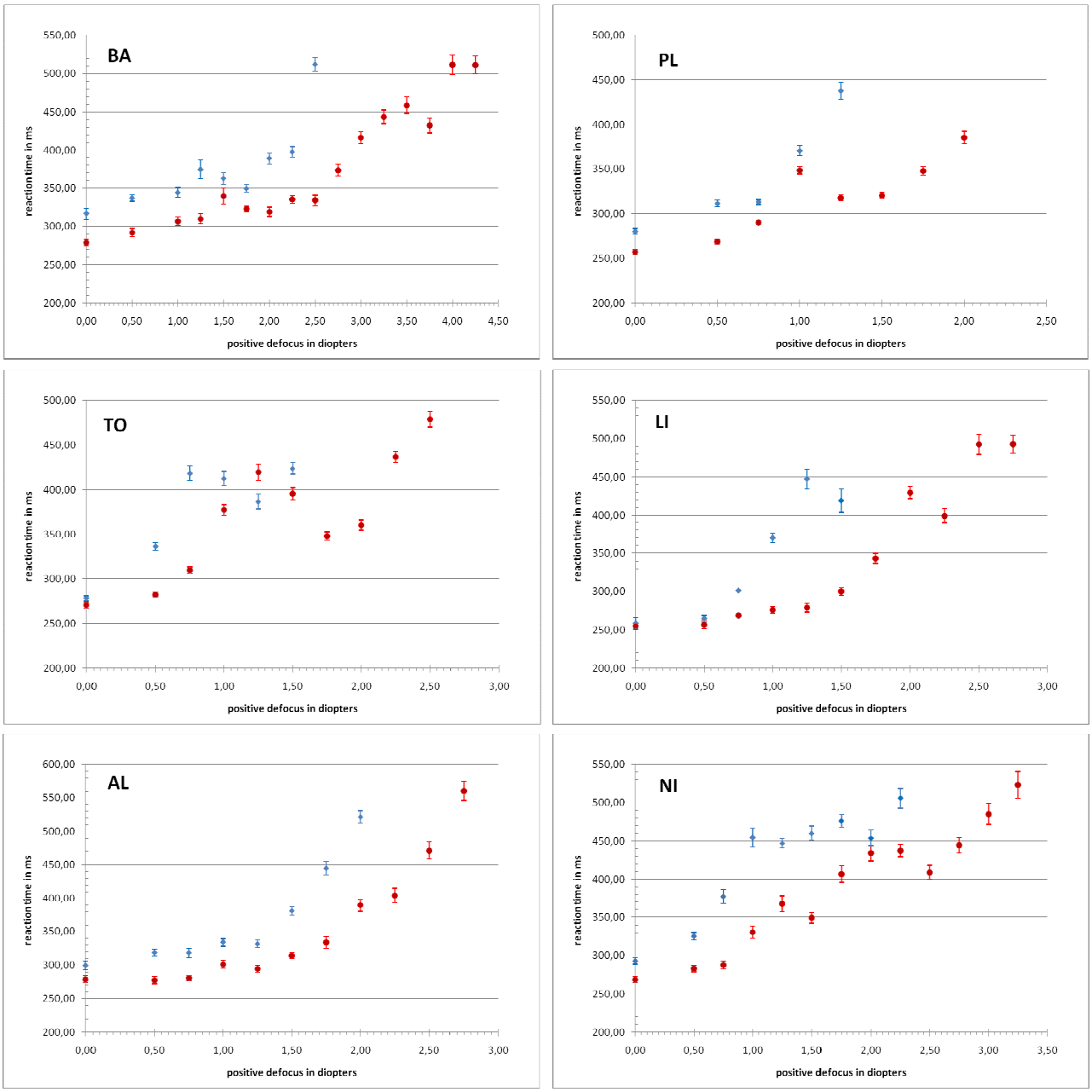

Figure 3.2.2: Reaction times (horizontal gratings) from all 6 subjects as a function of defocus for binocular (red squares) and monocular (blue diamonds) vision. Error bars indicate ± 1 standard error of the filtered raw data.

3.3 Converting simple reaction times to perceived contrast

Combining the contrast function determined in section 3.1 with the defocus data from section 3.2 allows a calculation of perceived contrast for different defocus levels. This is performed for each subject and viewing condition separately, using its individual contrast-RT functions and defocus-measurements. It is a way to quantify the effect of defocus in terms of contrast.

Formula [3.1] was converted to:

$$C=b/(T-T_i) \qquad [3.3.1]$$

With: T = reaction time

b = slope

C = Michelson Contrast

T_i = Intercept (T at highest C)

In order to get a correct perceived contrast value of 0.1 (10%) for zero defocus it was necessary to calibrate each Contrast-RT function. This was done by adjusting the intercept value Ti, so that C=0.1 for the reaction time at zero defocus (T0):

$$Ti=T-(b/0.1) \qquad [3.3.2]$$

Figure 3.3.1 shows the so calculated, averaged perceived contrasts for each defocus condition. It is obvious that the perceived contrast shows no constant difference between monocular and binocular viewing, especially for defocus above 1 dpt. This is expected because for each condition the corresponding contrast function has been used and since the intercept was calibrated for 10% C, the monocular Contrast-RT function “compensated” for the higher reaction times.

The similarity between monocular and binocular perceived contrast proves the contrast functions have been correctly calculated and that the approach in general is correct.

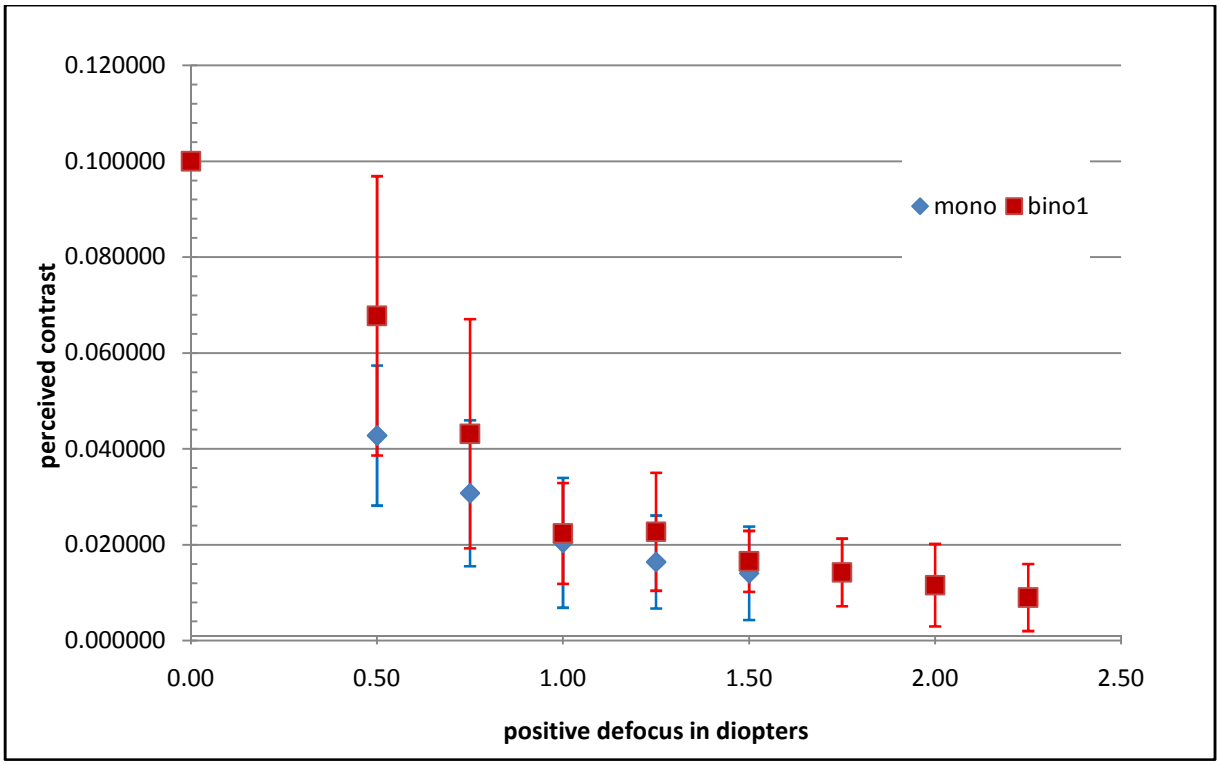

Figure 3.3.1: Average perceived contrast (horizontal gratings) from all 6 subjects as a function of defocus for binocular (red squares) and monocular (blue diamonds) vision. Error bars indicate ± 1 standard deviation of the filtered raw data.

To display the relative decrease of perceived contrast between binocular and monocular viewing, perceived contrast is calculated using the binocular contrast function only. Naturally the binocular graph does not change, but the monocular graph shifts towards lower contrasts because of its underlying higher reaction times.

As a consequence, the so calculated monocular perceived contrast values do not represent the contrast that the subject actually perceives during monocular viewing. Instead, these values show the simulated binocular contrast perception based on monocular reaction times and so the monocular perception in relation to binocular.

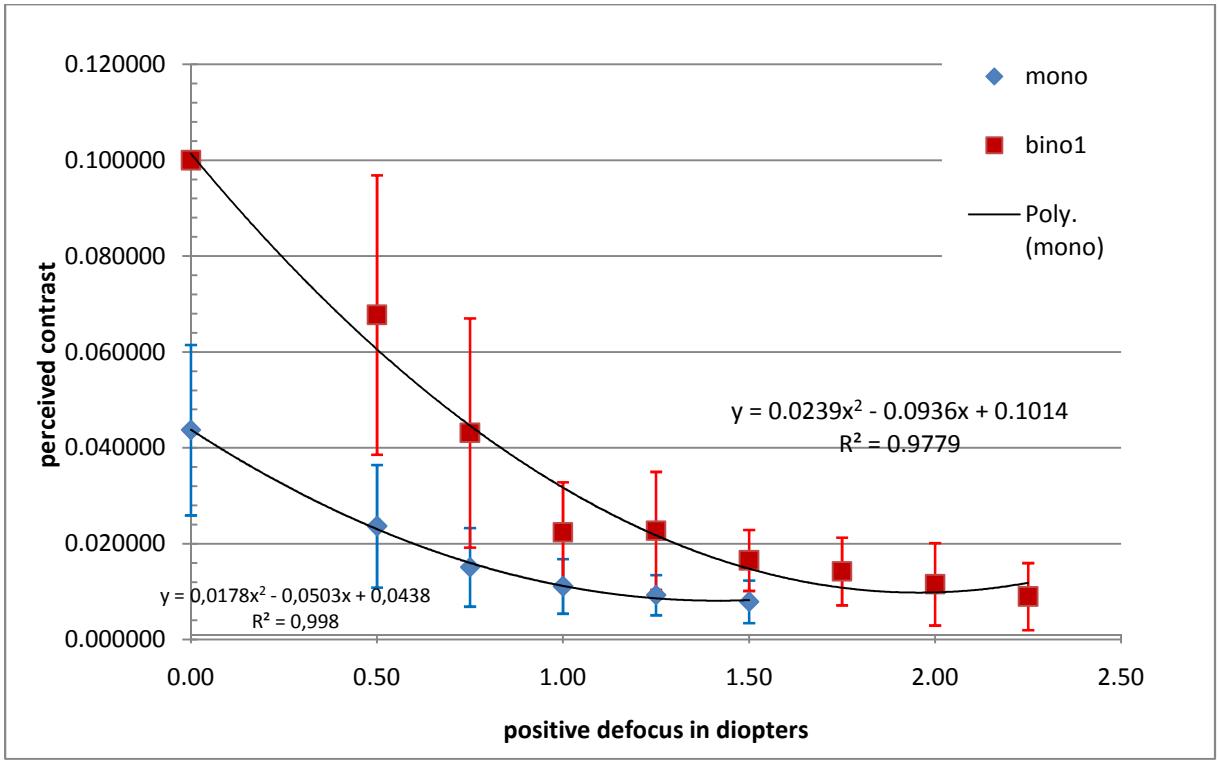

Figure 3.3.2: Average perceived contrast (horizontal gratings) from all 6 subjects as a function of defocus for binocular (red squares) and monocular (blue diamonds) vision, calculated using the binocular contrast function. Error bars indicate ± 1 standard deviation of the filtered raw data.

The binocular perceived contrast is at each defocus level significantly higher than the simulated monocular contrast. The threshold contrast of approx. 0.8% is reached binocularly at a 0.75 dpt higher defocus than monocularly.

Applying defocus to both eyes causes a certain decrease in perceived contrast. Our method can quantify this contrast loss.

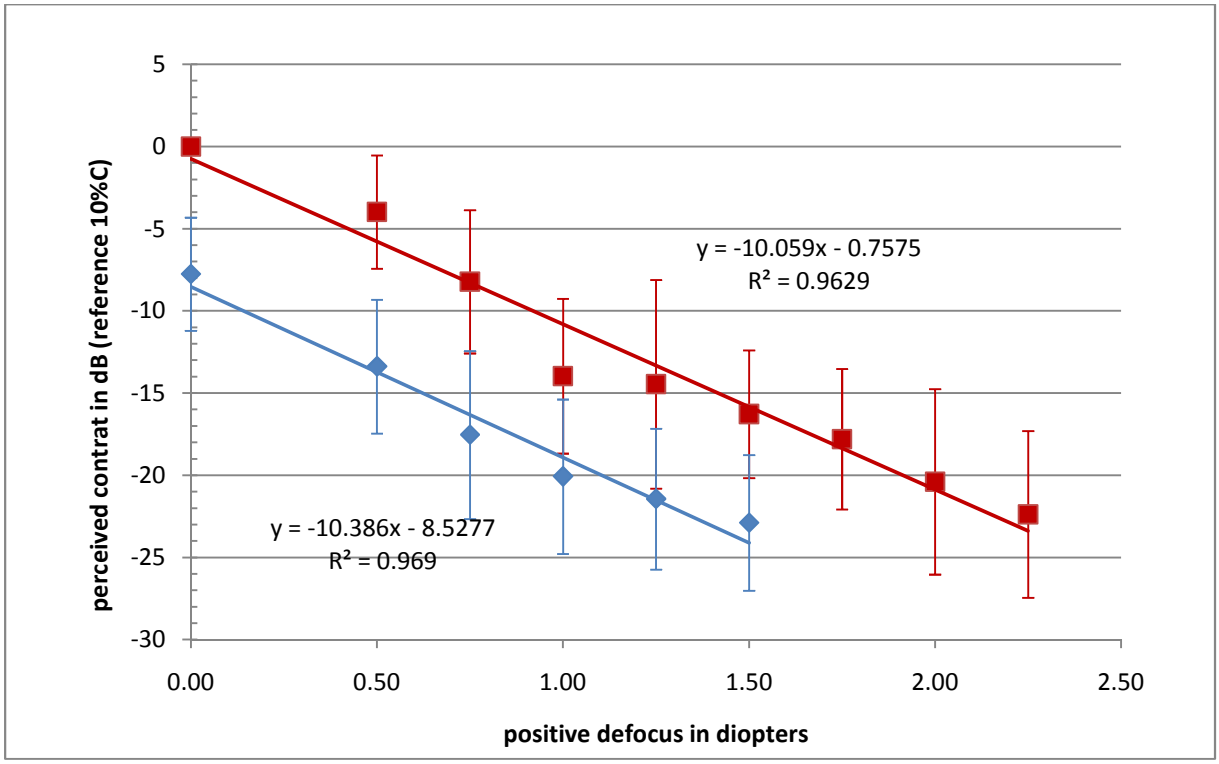

Figure 3.3.3: Average perceived contrast (horizontal gratings) in dB to 10% from all 6 subjects as a function of defocus for binocular (red squares) and monocular (blue diamonds) vision, calculated using the binocular contrast-RT function. Error bars indicate ± 1 standard deviation.

Figure 3.3.3 shows the linear fits of the perceived contrast data plotted in dB.

The functions display a nearly constant difference between binocular and monocular perceived contrast of about 8db. This graph shows again very clearly the previously mentioned binocular advantage of 0.75 dpt defocus.

3.4 Binocular summation factor

Many publications have reported an increase in binocular visual performance by factors reaching from 1.1 to more than 3 compared to monocular.

In detail, Cagenello, Arditi et al.(Cagenello, Arditi et al. 1993) reported a binocular summation factor of 1.11 for (supra threshold stimuli) visual acuity optotype measurements and Campbell and Green (Campbell and Green 1965) found a factor of 1.4 for contrast sensitivity at near threshold stimuli.

Higher summation factors have been reported for electrophysiological experiments (Fischer and Kruger 1979) and visual evoked potentials at +2D defocus increase binocularly by more than 300% (Plainis, Petratou et al.).

Looking at the RT data only, one can see that the factors between monocular and binocular values are comparably low for a near threshold stimulus. The reason lies partly in the composition of a simple reaction time (perception time + motor time) and partly in the non-linear relation between RT and contrast. Because simple visual reaction times consist not only of a visual dependent component, but also an individually different, fixed time for signal processing and motor response it seems more reasonable to describe the binocular advantage comparing perceived contrast. Furthermore our findings in section 3.1 have proved the linear function between RT and 1/contrast and in section 3.3 we demonstrated the conversion of RTs to perceived contrast.
Using the perceived contrast data, calculated in section 3.3 it is possible to calculate the increase of contrast sensitivity for each subject individually (Binocular summation factor) using following formula:

$$F = \frac{\frac{C_{B1}}{C_{M1}} + \frac{C_{B2}}{C_{M2}} \ldots + \frac{C_{Bn}}{C_{Mn}}}{n} \qquad [3.6.1]$$

C_{Bn} = Binocular perceived contrast for defocus step n

C_{Mn} = Monocular perceived contrast for defocus step n

F = Binocular summation factor

Subject	Binocular summation factor
BA	2,14
PL	1,91
TO	1,71
AL	3,31

LI	3,17
NI	2,34
MEAN	**2,43**

Table 3.4.1: Average Binocular summation factors for each subject (horizontal grating)

3.5 Depth of focus determination

Using the data it is possible to calculate “positive” depth-of-focus using a certain blur criterion.

A wide range of depth-of-focus values can be found in literature. However, Atchison, Charman et al. (Atchison, Charman et al. 1997) reported a subjective depth of focus in a range from 0.28 to 0.43.

Looking at the monocular graph in figure 3.4.1 one can see that at 300ms a defocus of 0.34 D is reached. This defocus value seems to be reasonable and so the blur criterion is chosen arbitrary at a reaction time of 300ms. Looking at figure 3.4.1 it is obvious that the binocular depth of focus is significantly higher than the monocular.

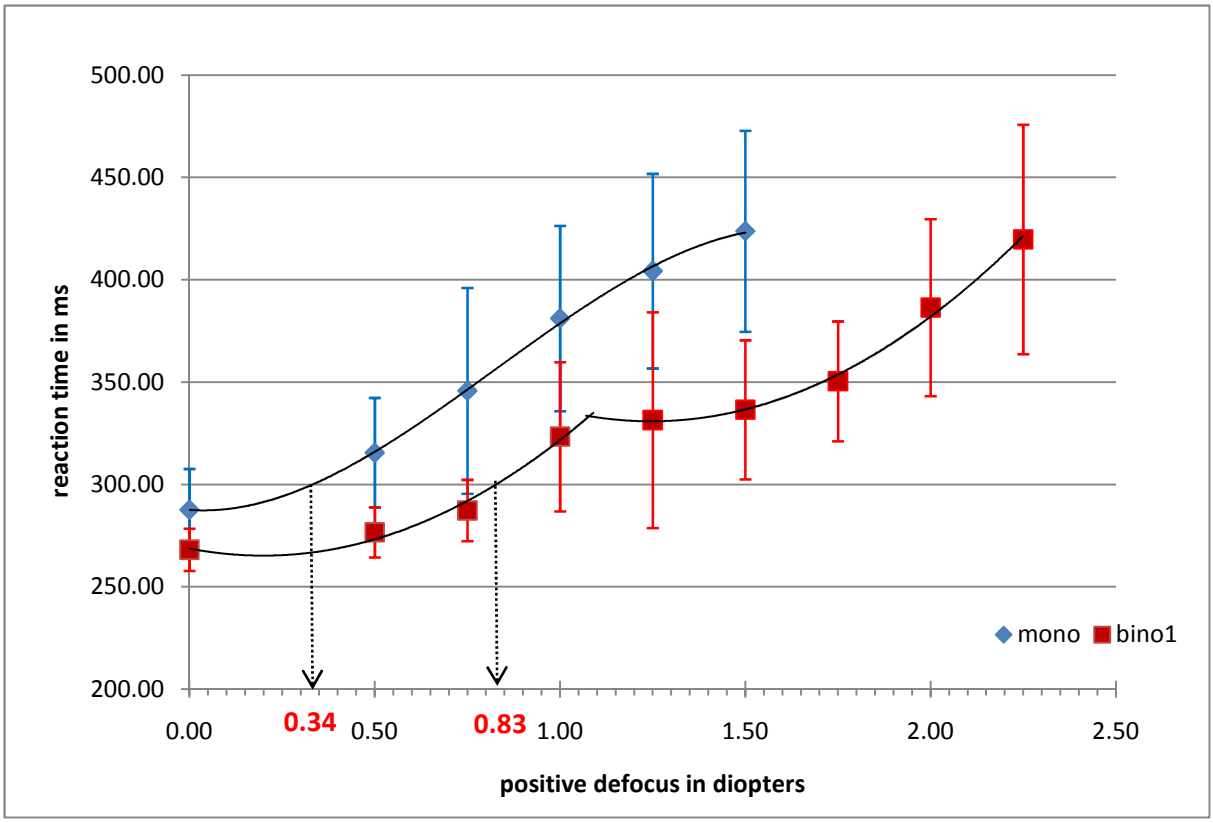

Figure 3.4.1: Averaged reaction times (horizontal gratings) from all 7 subjects as a function of defocus for binocular (red squares) and monocular (blue diamond) vision. Arrows indicate the positive depth of focus for a 300ms blur criterion. Error bars indicate ± 1 standard deviation.

The blur criterion for each single subject has been determined similarly, by finding a reasonable defocus value for monocular viewing and subsequently a blur criterion in milliseconds RT.

The RT graphs for single subjects look naturally different from the group values and calculated depth of focus values may vary. Figure 3.4.2 shows the data for all 6 subjects and although the depth-of-focus values are different, binocularity provides always a significant advantage.

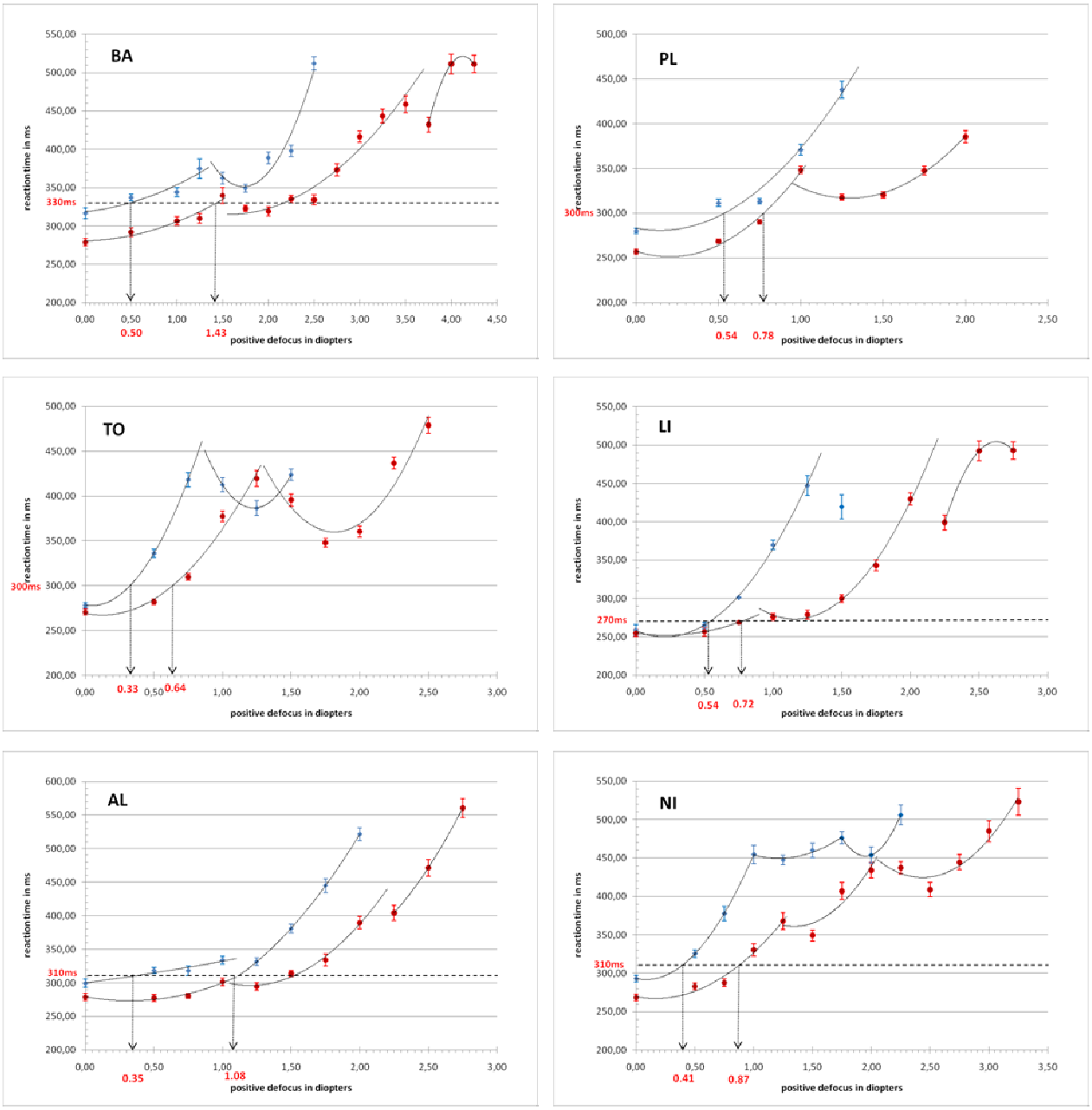

Figure 3.4.2: Reaction times (horizontal gratings) from all 6 subjects as a function of defocus for binocular (red squares) and monocular (blue diamonds) vision. Arrows indicate the positive depth of focus. The blur criterion in ms and the monocular and binocular depth of focus are noted in red. Error bars indicate ±1 standard error.

The average depth-of-focus for monocular is 0.44dpt and for binocular 0.92dpt. The resulting average binocular to monocular difference is found to be 0.48dpt with a range from 0.18dpt to 0.93dpt.

3.6 Comparison between horizontal and vertical gratings

During the first stage of the experiments it became obvious that the subjects had difficulties to overlap the binocular images of vertical gratings at higher levels of defocus. When defocus reached a certain level, it became difficult to see the crosshair target and align eye-vergence.

In order to avoid artificially high reaction times for binocular viewing due to this missing overlap, it was decided to use horizontal gratings instead. Even when the vergence of the eyes is not perfectly aligned to the correct viewing distance, a horizontal grating should guarantee a signal-increasing image overlap.

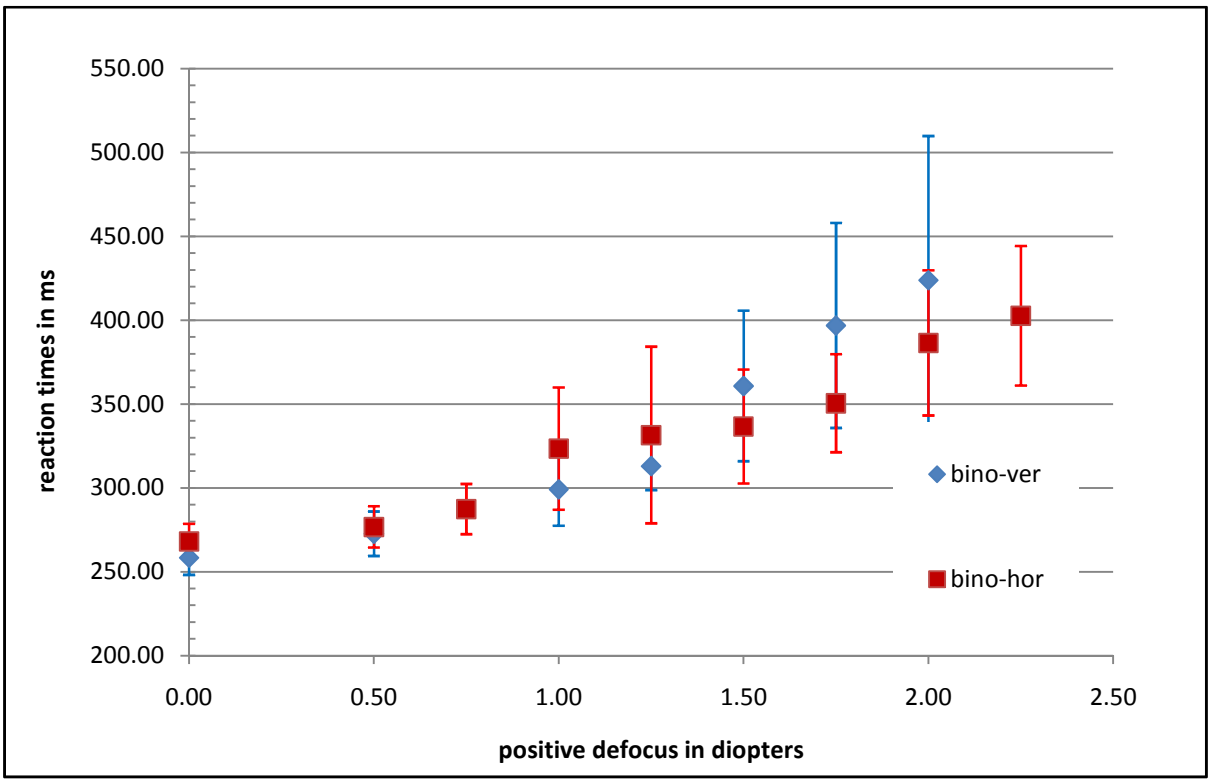

Figure 3.5.1: Averaged binocular reaction times from all 6 subjects as a function of defocus for horizontal (red squares) and vertical (blue diamond) gratings. Error bars indicate ± 1 standard deviation.

The subjective observation could be experimentally proved as seen in figure 3.5.1. Between 0 and +1.25dpt vertical gratings produce faster binocular reaction times. RTs for vertical

gratings show a sudden increase above the values for horizontal gratings at a defocus of +1.5dpt and above. In contrast, for monocular reaction times vertical gratings have always a lower or equal RT than horizontal gratings.

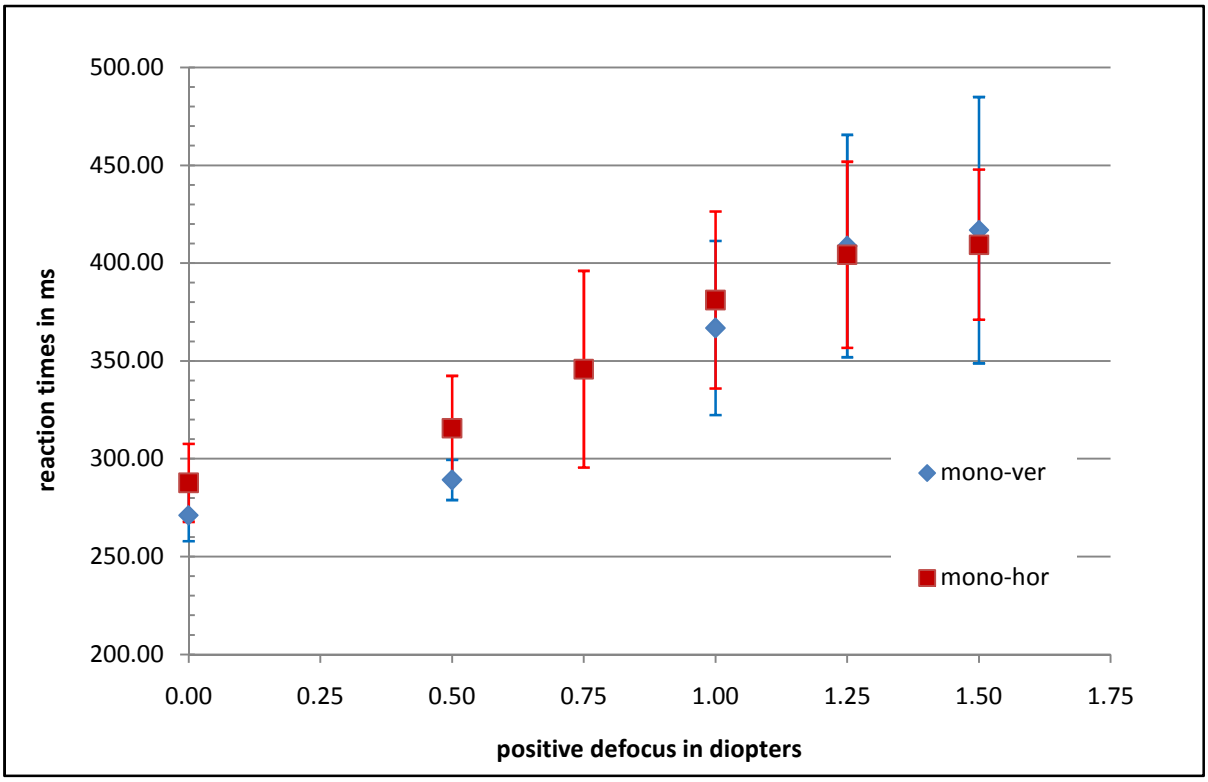

Figure 3.5.2: Averaged monocular reaction times from all 6 subjects as a function of defocus for horizontal (red squares) and vertical (blue diamond) gratings. Error bars indicate ± 1 standard deviation.

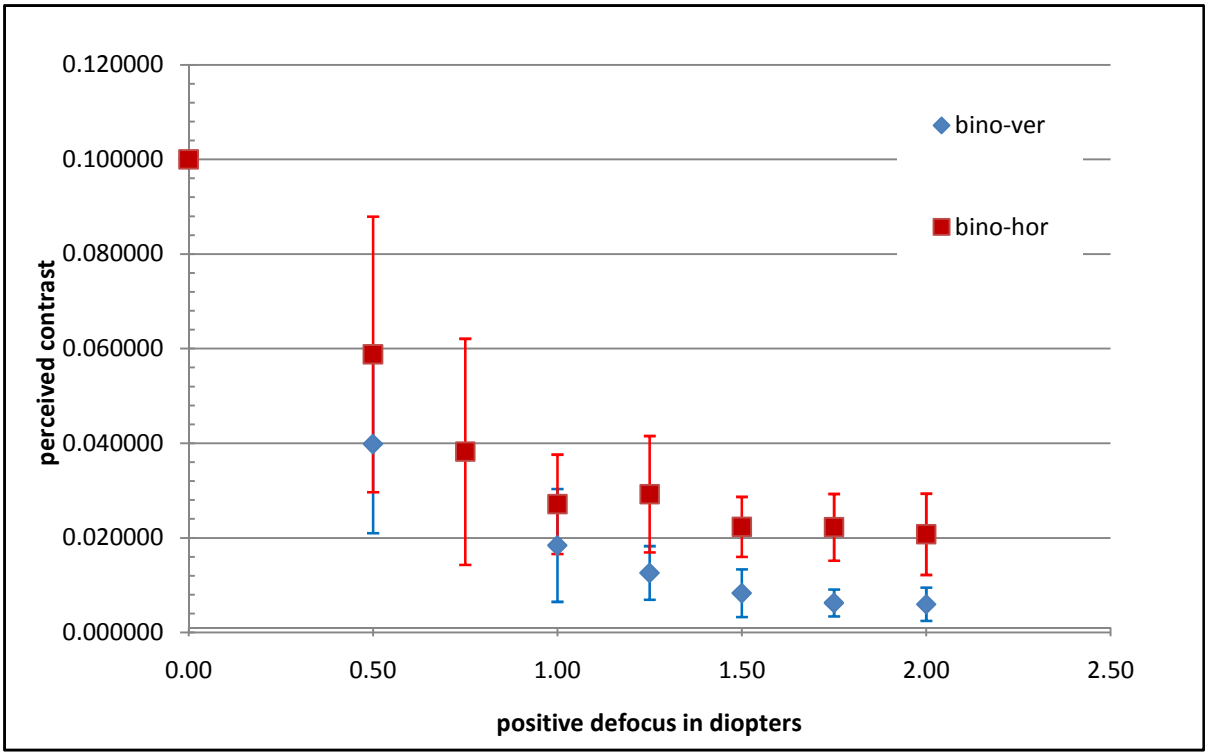

Figure 3.5.3: Averaged binocular perceived contrast from all 6 subjects as a function of defocus for horizontal (red squares) and vertical (blue diamond) gratings. Error bars indicate ± 1 standard deviation.

Interestingly, when converted to perceived contrast as described in 3.4, horizontal gratings perform better at each defocus level. Obviously the contrast function did not compensate the higher reaction times at +1.5dpt defocus as is the case for monocular viewing.
This can be explained by the method that the RT-C function is obtained. The RT-contrast function is measured with best spectacle correction. The subject sees the monitor and the target-cross clearly, so that sufficient oculomotor adjustments can perfectly overlap the binocular image. Insufficient overlap appears only during the defocus experiment and at a certain level of defocus, when monitor and target-cross can not bee seen clear enough anymore.

3.7 Aspects of negative defocus

Two of the subjects have also been measured with negative defocus. Figure 3.7.1 illustrates the binocular and monocular reaction times for negative and positive defocus for subject PL. These measurements have only been performed with vertical gratings.

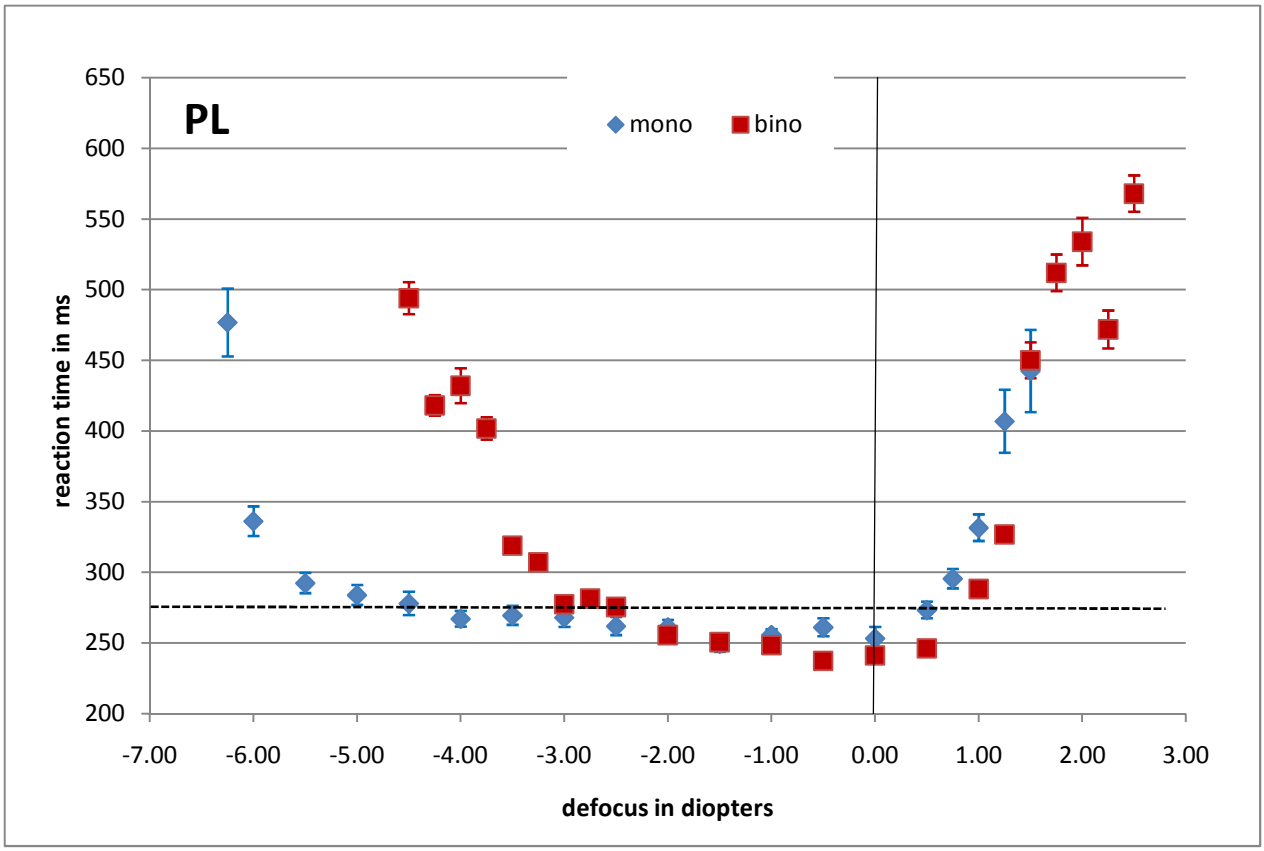

Figure 3.7.1: Reaction times (vertical gratings) from subject PL as a function of defocus for binocular (red squares) and monocular (blue diamond) vision. The dotted horizontal line indicates 275ms reaction time. Error bars indicate ± 1 standard error.

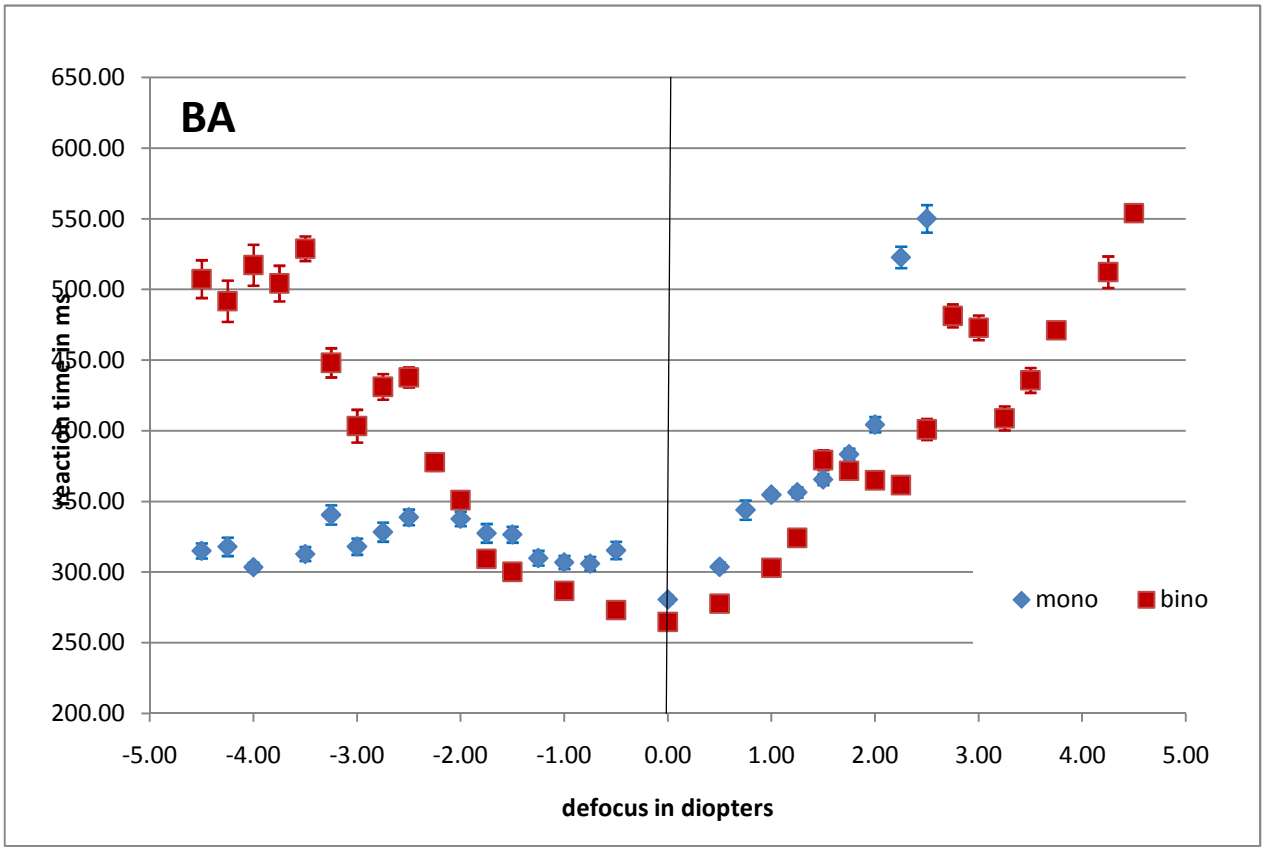

Figure 3.7.2: Reaction times (vertical gratings) from subject BA as a function of defocus for binocular (red squares) and monocular (blue diamond) vision. Error bars indicate ± 1 standard error.

Contrary to our previous findings monocularity allows a much higher negative defocus than binocularity, which may be due to insufficient image overlap with binocular vision. Defining the accommodative range as the negative defocus value at which the reaction time reaches 275ms for subject PL and 350ms for subject BA , the respective accommodative ranges reach -2.50 dpt and -2.00 dpt for binocular as well as -4.25 dpt and higher than -4.50 dpt for monocular viewing.

Comparing the accommodative range for horizontal and vertical gratings gives a similar result as for positive defocus. At low defocus RTs for vertical gratings are better and they become higher than horizontal at approximately -1.75dpt defocus. Noteworthy is the higher scatter of the vertical data, which may be caused by the fluctuations in binocular image quality as described in section 4.6.

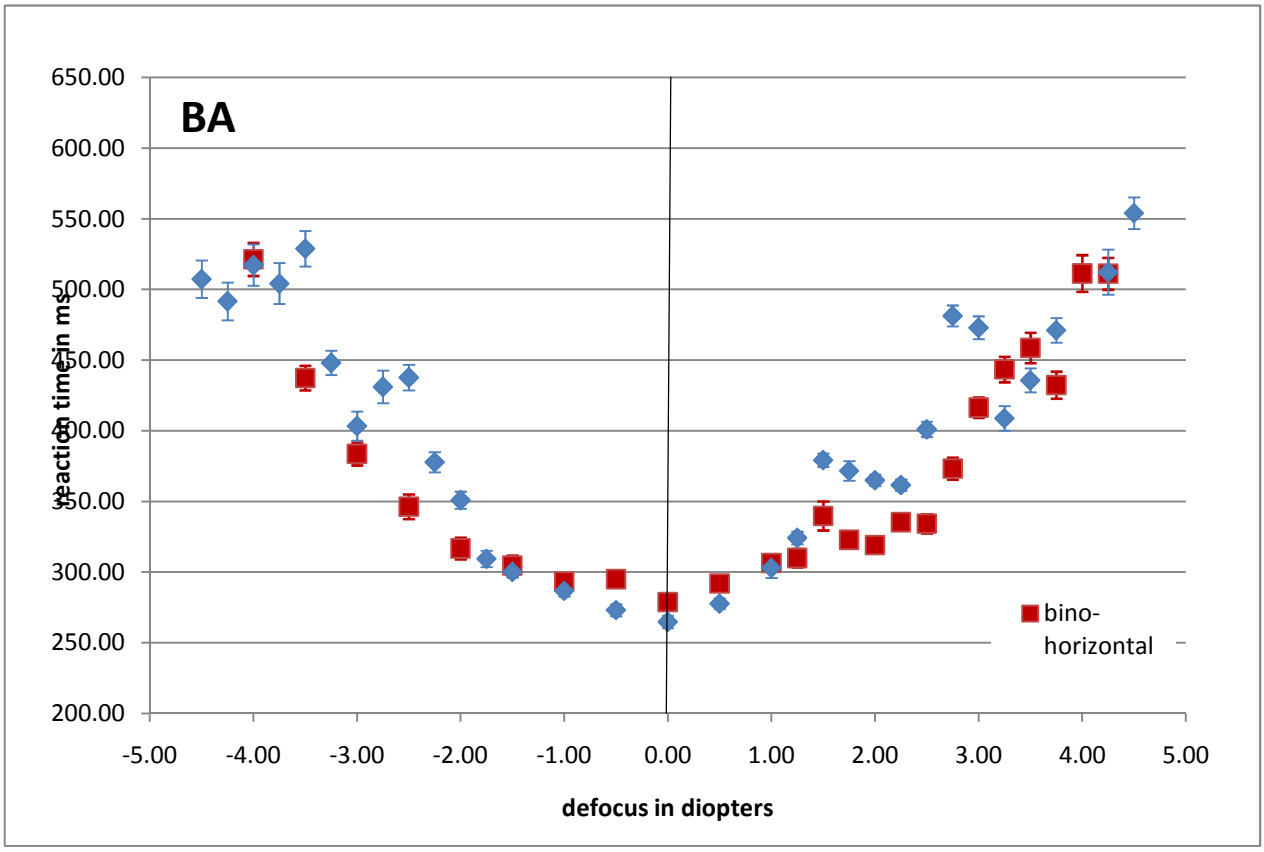

Figure 3.7.3: Binocular reaction times from subject BA as a function of defocus for horizontal (red squares) and vertical (blue diamond) gratings. Error bars indicate ± 1 standard error.

4 Discussion

4.1 Contrast-RT function

Our results on the the Contrast-RT function (section 3.1) correlate very well with previously published findings (Harwerth and Levi 1978), (Plainis and Murray 2000). The conversion to RT vs. 1/C graphs results to a well fitting linear regression for all subjects, allowing subsequently the mathematic description of the correlation between contrast and RT (Contrast-RT function).

The slope values of the Contrast-RT function are of special interest, since they form a measure of contrast sensitivity (CS). The slope values in tables 3.1.1 and 3.1.2 show significant difference between vertical and horizontal gratings and between monocular and binocular viewing. To quantify the later difference, a slope-ratio is included in the tables. This ratio is constantly higher for vertical gratings than for horizontal, implying a higher binocular contrast sensitivity advantage for vertical gratings. This can not be explained by differences in the binocular image overlap since the ratio shows nearly the same difference for monocular and binocular viewing.

Apart from this higher ratio, the slopes for vertical gratings are lower than for horizontal, implying a higher CS for vertical gratings. A possible explanation could be the neural advantage for certain grating orientations. Oblique gratings cause a lower contrast sensitivity than vertical or horizontal , but there seems to be no significant difference between horizontal and vertical gratings (Campbell, Kulikowski et al. 1966).

Finally, remaining astigmatism and high order aberrations may at least contribute to that difference. The measured group was rather small and it is very likely that most of the subjects had a slight remaining “with the rule” astigmatism. This type of astigmatism causes an improved perception of vertical vs. horizontal gratings. Even when corrected during the experiment, higher astigmatism causes a lasting decrease of visual performance for horizontal gratings due to neural mechanisms (Mitchell and Wilkinson 1974).

It is interesting to note, that the average slope–ratio for horizontal gratings is very close to the binocular summation factors of sqrt2 (1.414), that have been found for contrast sensitivity in early experiments (Campbell and Green 1965).

4.2 Comparison between monocular- and binocular RT with positive defocus

The RT vs. defocus graph shown in figure 3.2.1 appears to be biphasic for binocular viewing. Due to the small sample size it is difficult to conclude if it is a universal feature of RT-defocus graphs, or if it an averaging artefact.

Similar biphasic relations between RT and contrast have been published earlier (Harwerth and Levi 1978; Harwerth, Boltz et al. 1980). The biphasic appearance was found to be due to different detecting channels in the visual pathway (sustained-transient / Parvo-Magno). In our case it seems unlikely that the same mechanism may be responsible. Our grating of 4c/deg had a maximum contrast of 10% when zero defocus was applied. According to Harwerth and Levi (Harwerth and Levi 1978) and Plainis and Murray (Plainis and Murray 2000), at these contrast levels (and for 4c/deg) only the transient (or Magno-) channel should be responsible for the measured RT. However, all these earlier studies have been performed monocularly and as we have seen already in section 3.3 and 3.4 binocular vision provides a significant perceived contrast improvement (average factor of 2.43).

Applying the average binocular summation factor found in section 3.4 to the averaged monocular perceived contrast (figure 3.3.1) allows us to evaluate which binocular contrast level corresponds to 10% monocular perceived contrast. Figure 3.2.1 shows the transition from one to the other phase at approximately +1dpt defocus. Average perceived monocular contrast for 1dpt defocus is 0.033 or 3.3% and multiplied by 2.43 we get a value of 0.080 or 8%. This is not very far from the published 10% borderline and so, a transient-sustained channel mechanism could be responsible for the biphasic appearance of the averaged binocular Defocus-RT graph.

Apart from the bimodal graph of the averaged data, the individual graphs for each subject appear mostly multimodal. A reasonable explanation for this multimodality seems to be the phenomenon of spurious resolution (see 1.3 for details). The non-monotonous decrease of contrast for increasing defocus could explain the shape of a single subjects Defocus-RT graph. Inter-subject differences can easily be explained by differences in high order aberrations (Smith 1982; Atchison, Woods et al. 1998; Tahir, Parry et al. 2009).

The reason for the big differences of acceptable blur (defocus) is another question that arises from these data. One reason may be the individual high order aberrations, especially the amount of

spherical aberration. A measurement of high order aberrations for each subject would be necessary to evaluate this assumption. Unfortunately due to technical reasons a measurement of high order aberrations was not possible during this work. However, the differences in blur acceptance could have also a neural explanation. Subject BA is a low myope of about 1.75dpt, but never wears any form of correction (glasses or contact lenses) and shows the highest range of accepted defocus. Due to the small sample and the design of this study, it is impossible to conclude that a neural blur adaptation is responsible for increased defocus acceptance. A future study should investigate this relation in detail.

Another aspect of our findings is the absolute reaction time difference and their implication for driving, or similar time critical tasks as investigated in detail by Plainis and Murray (Plainis and Murray 2002).

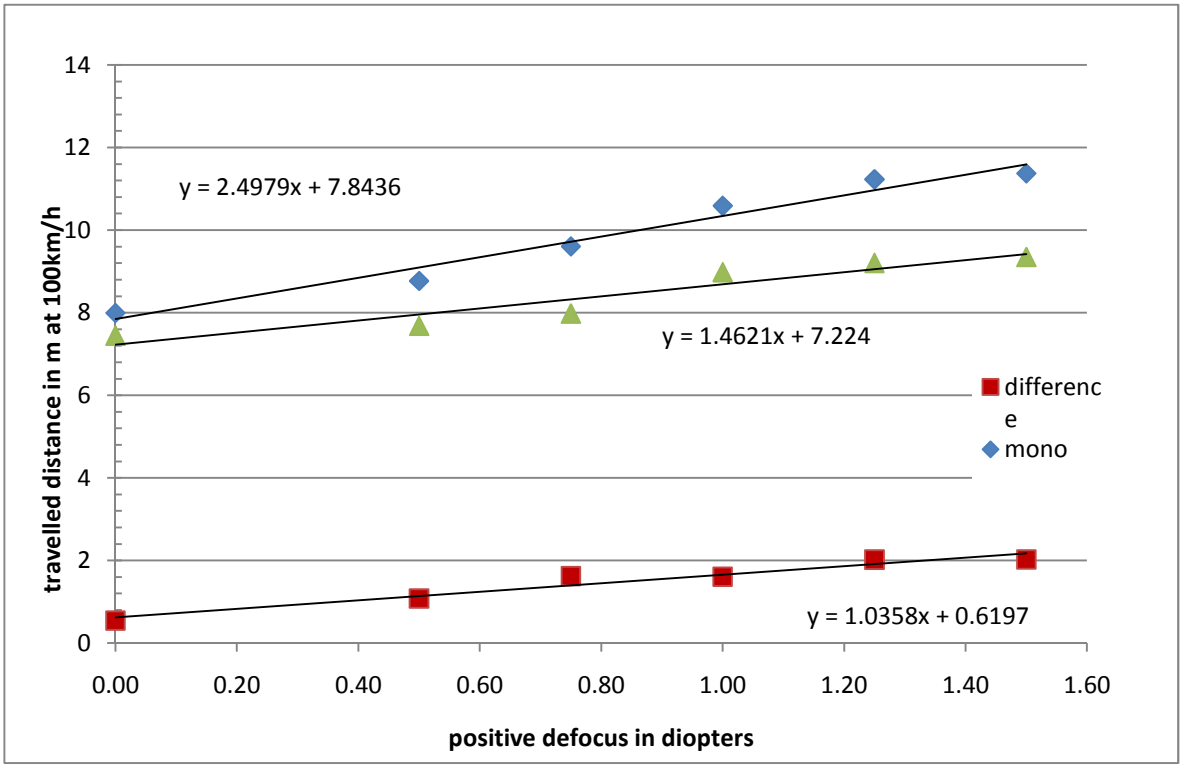

Figure 4.2.1: Travelled distance at 100km/h during the average measured RT for binocular (green triangles), monocular (blue diamonds) and the difference between them (red squares). All values are for horizontal gratings.

Defocus increases reaction times and subsequently stopping distances significantly. This is especially valid for monocular viewing, where only one dioptre defocus causes a nearly 2.5m increase (at 100km/h). The faster reaction time for binocular viewing in presence of e.g. 1.5dpt defocus (refractive error) can shorten the stopping distance at an emergency brake from 100km/h by 2 m.

Drivers with only one functional eye (e.g. amblyopes) have not only the disadvantage of decreased visual field and reduced distance judgement they may also have comparably higher reaction times. That exposes them to a much higher safety risk, especially while driving under non ideal conditions.

All this of course assumes that reaction times for our specific stimulus are comparable to real life visual stimuli. This may depend mostly from the contrast and the scenery and so this values may be more valid for lower contrast environments like during rain or fog, or at night time.

4.3 Converting simple reaction times to perceived contrast

The conversion of RTs to perceived contrast allows us to quantify the binocular advantage or monocular disadvantage. A similar approach has been used earlier to convert certain RT values to perceived contrast (Blake, Martens et al. 1980).

As described in section 3.3, the need for calibration of the RT-contrast function makes a direct comparison of monocular or binocular data impossible. Our approach to use the binocular RT-contrast function to calculate perceived contrast not only for binocular defocus data but also for monocular seems to be a reasonable accurate way to determine the actual contrast gain of binocular vision.

Apart from the comparison of binocular with monocular perceived contrast it is interesting to see the quantitative contrast decrease when defocus is applied. Figure 3.3.2 illustrates the perceived contrast change vs. defocus. Until 1.00dpt defocus, both monocular and binocular perceived contrast decreases nearly linearly. A further increase of defocus leads to an asymptotic graph and a substantial change in defocus is perceived only as a small contrast change. The asymptotic function starts at about 1.50dpt for monocular and 2.00dpt for binocular viewing. At these levels of defocus the detection limit for our grating stimulus is almost reached. Higher defocus decreases the stimulus contrast below detection level and no valid measurements are possible. The last valid RT measurements are very different for each subject as seen in figure 3.2.2 . However, the conversion of these values into perceived contrast allows us to calculate a detection threshold for this specific stimulus. This averaged perceived contrast is 0.0066 or 0.66% (±0.44) for binocular and 0.0121 or 1.21% (± 0.53) for monocular. Relative to 100% contrast this means a binocular contrast threshold of

43.6dB and a monocular contrast threshold of 38.4dB. These values are very similar to those we have found using method of adjustment and this proves the reliability of our RT to contrast conversion.

4.4 Binocular summation factor

The factor of binocular summation has been measured in the past using different, mostly near-threshold, methodologies (Campbell and Green 1965; Home 1978; Cagenello, Arditi et al. 1993), while only a few have been using reaction times for this task (Blake, Martens et al. 1980; Harwerth, Smith et al. 1980). The published binocular summation factors range from 1.11 to more than 3, depending substantially on the type of stimulus used (i.e. its contrast) and the visual parameter tested. Therefore it is difficult to compare these factors and it turns out that binocular summation has to be differentiated for certain stimulus and response types. The factors we have found (table 3.4.1) are relatively high, especially compared to other published supra-threshold tasks. However, the factors found in this study are similar to earlier findings using simple reaction times based on RT to contrast conversion (Blake, Martens et al. 1980).
It would be interesting to see, if the significant differences between subjects are correlated with other aspects of binocular performance, like stereopsis or eye dominancy.

4.5 Depth of focus determination

Using a reasonable blur criterion, it may be possible to calculate the positive depth of focus using our RT data with certain accuracy. Although it is a psychophysical (behavioural) method, the measurement can be assumed objective, since there is no subjective blur criterion involved. Most published data on depth-of-focus are for single eyes only. This makes sense in terms of technical optics, but since our visual system uses typically both eyes to perceive the environment it may be useful to actually measure binocular depth of focus. It is especially relevant when investigating presbyopia and the success of its treatment methods. Measuring binocular depth-of-focus using

psychophysical / behavioural methods provides objective results that may reflect best the actual visual experience.

Our experiments have been performed with natural pupils and pupil size is naturally not constant for each viewing condition. Furthermore, pupil size has a significant influence on depth of focus, especially in the range until 4mm (Atchison, Fisher et al. 2005). Considering these facts, we investigated if the increased depth of focus for binocular vision could be simply explained by smaller pupils. Figure 4.5.1 illustrates the pupil sizes for all subjects, measured under the exact same conditions like the RT experiment was performed.

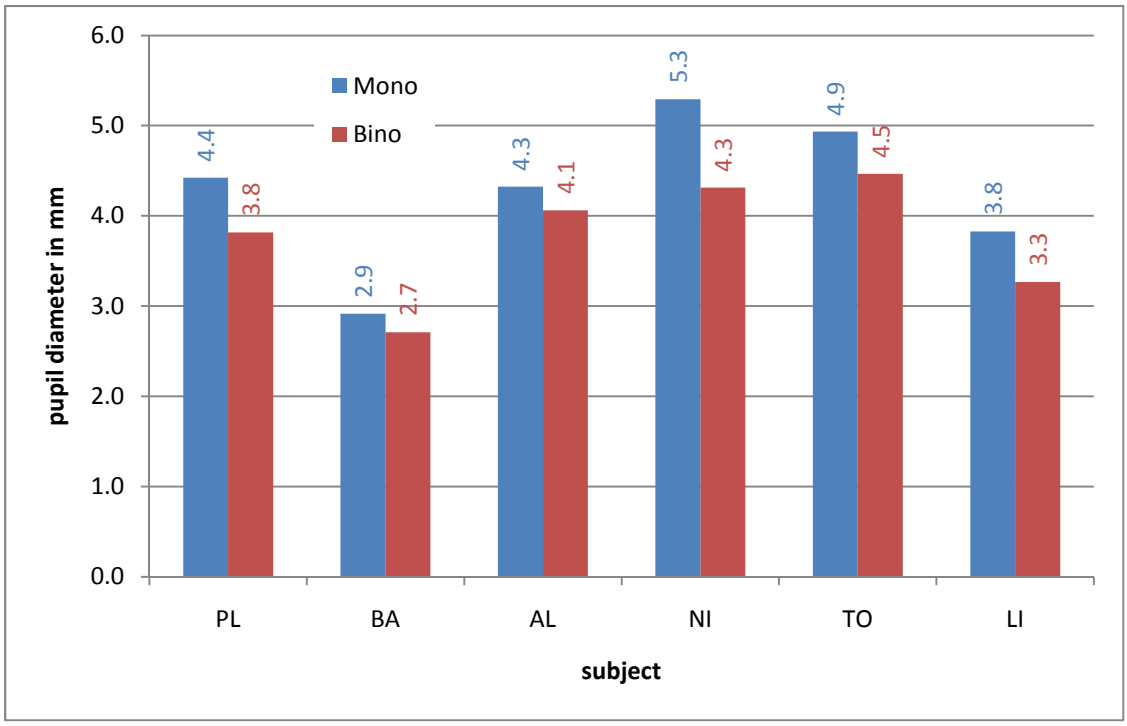

Figure 4.5.1: Pupil sizes of each subject for monocular (blue) and binocular (red) viewing.

The above data show that pupils are generally smaller when looking at the stimulus-monitor binocularly. The mean difference between binocular (3.8mm) and monocular (4.3mm) viewing is 0.5mm. A conversion of this averaged value to a depth of focus difference is not possible, because depth-of-focus vs. pupil size is a non-linear function (see figure 4.5.2). To illustrate the effect of pupil size, the pupil size data from subject TO have been added to figure 4.5.2 and it can bee seen that this small pupil size difference causes 0.12dpt difference in depth of focus. Although this is not very accurate, because the graph was created from an average of 5 subjects only, and there may be a high inter-subject variation it is not a neglectable effect. Assuming the value is correct, from the

calculated binocular/monocular depth of focus difference of 0.31dpt; only 0.19dpt is due to binocular effects. Similar calculations can be done for each subject and it will be obvious that the smaller pupil size contributes to the higher binocular depth of focus.

Additionally it should be considered that the refractive error of each eye is only corrected within an accuracy of 0.25dpt. Refractive differences between the eyes may also have contributed to the increased binocular depth of focus.

Future experiments investigating binocular depth of focus should take pupil size and optical aberrations into account. Ideally an artificial pupil and adaptive optics should be used to rule out any optical effects in favour of binocular depth of focus.

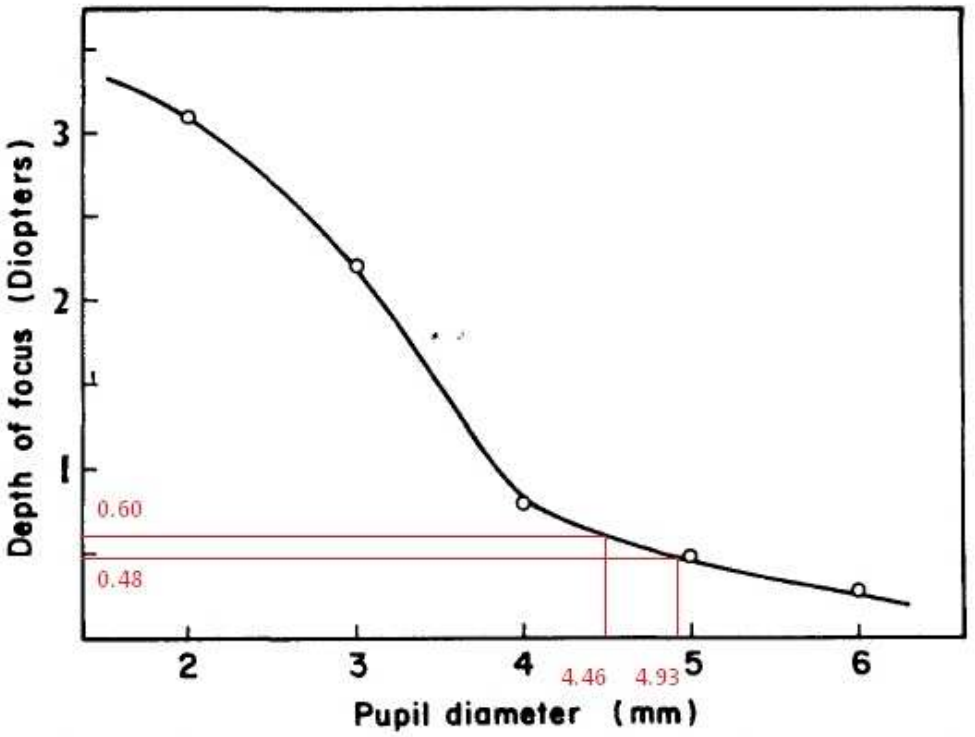

Fig. 8. Depth of focus as a function of pupil size. The mean results for five emmetropic subjects computed from their wave-aberration results.

Figure 4.5.2: Depth of focus as function of pupil size (from (Artal 1990)). The red lines indicate monocular (4.93mm) and binocular (4.46mm) pupil size and their respective depth of focus for subject TO.

4.6 Comparison between horizontal and vertical gratings

The orientation of a sinusoidal grating stimulus has a noticeable influence on its detectability. While oblique gratings are more difficult to detect, there seems to be no significant difference between horizontal and vertical gratings (Campbell, Kulikowski et al. 1966). Our RT data (figures 3.5.1 and 3.5.2) support this finding since the monocular- and near-focus binocular RTs are only slightly lower for vertical gratings. As mentioned before, this small advantage may be explained by a small residual astigmatism “with the rule” that can be frequently found in the population.

The interesting aspect we found is the sudden increase of vertical RTs compared to horizontal, at about 1.5dpt defocus. The explanation is most probably that at high defocus levels the eyes do not find a cue to adjust their vergence to the correct viewing distance. Monitor and target-crosshair are so much blurred that the viewing distance cannot be detected by the subject’s visual system. This is of course valid for vertical and horizontal grating stimuli, but the resulting error in image overlap shows different consequences. As illustrated in figure 4.6.1 a horizontal error in image overlap as caused by eye vergence can create very different combined images. It may cause an effective contrast decrease for vertical gratings, depending on the phase difference, while horizontal gratings still show a contrast increase.

Figure 3.5.1: Simulation of insufficient binocular image overlap of a vertical grating (left) and horizontal grating (right).

A similar observation of reduced binocular performance due to weak accommodative vergence cues has been made earlier (Home 1978). However, the here presented relation between grating orientation and binocular summation at blur is a novel observation. It should have consequences for the future investigation of binocularity using gratings or similarly oriented stimuli.

4.7 Aspects of negative defocus

The large difference between the binocular and monocular accommodative ranges found in section 3.7 can only be explained by the fact that the target was at 3m distance. When viewing binocularly, the accommodation process of the eyes is accompanied by a synchronous vergence eye movement that adjusts viewing direction to nearer distances. This in turn causes diplopia for the distant target and subsequently binocular inhibition, lower perceived contrast and higher reaction times.

The effect is obviously more pronounced than the one described in 4.6 and the use of horizontal gratings did not cause a significant improvement of accommodative range (figures 3.7.2. and 3.7.3).

This can be expected because the accommodative cues for near targets are very strong and the resulting vergence is much higher than expected for positive defocus.

5 Conclusions

The measurement of simple visual reaction times has proved to be a reliable and accurate way to determine the quality of visual perception. A big advantage of this method is the objective data acquisition and the possibility to use supra-threshold stimuli.

A very important finding for future experiments on binocularity is the influence of grating orientation when the stimulus detectability decreases and the eyes have no cue for viewing distance.

Our findings have proven the linearity of 1/contrast vs. RT functions and the use of these functions for converting reaction time measurements to perceived contrast. This methodology can be used in future experiments, where a quantification of the perceived contrast is desirable.

It has been shown that the determination of binocular depth of focus and accommodative range is possible by RT measurements. A promising application would be the evaluation of treatments for presbyopia. However, it is necessary to increase the accuracy and in future studies the pupil size and the exact optical aberrations should be considered when comparing monocular and binocular depth of focus. Binocular measurements of accommodative range need a completely different experimental setup, where the viewing distance matches the eye vergence.

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