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Symmetric visual response to positive and negative induced spherical defocus under monochromatic light conditions

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ABSTRACT

The purpose of the study was to investigate the sign-dependent response to real and simulated spherical defocus on the visual acuity under monochromatic light conditions. The investigation included 15 myopic participants with a mean spherical equivalent error of -2.98 ± 2.17 D. Visual acuity (VA) was tested with and without spherical defocus using the source method (simulated defocus) and the observer method (lens-induced defocus) in a range of $\pm$ 3.0 D in 1.0 D steps. VA was assessed using Landolt C's, while the threshold was determined with an adaptive staircase procedure. Monochromatic light conditions were achieved using band pass filters with a wavelength of 450 ± 2 nm, 530 ± 2 nm and 630 ± 2 nm. Results showed that the reduction of VA was significantly different under blue lighting conditions, when compared to the green and red light conditions. No significant difference in the reduction of the VA was found between the positive and the negative sign of defocus for all lighting conditions. The agreement for the VA between the source and observer method was significantly dependent on the wavelength as well as on the level of defocus. To conclude, under monochromatic light conditions, myopes show a symmetric sign-dependency regarding the influence of spherical defocus on visual acuity. The observed results indicate that the human visual system is capable of integrating the chromatic differences in refraction to distinguish between the signs of defocus.

1. Introduction

The assessment of subjective visual performance, e.g., visual acuity or contrast sensitivity, in the presence of optically induced aberrations is a widely studied measure and applied in every assessment of the subjective refractive error (Benjamin, 2006). It could be used for example, to judge the goodness of an optical correction (Hayashi, Hayashi, Nakao, & Hayashi, 2000; Kasper, Bühren, & Kohnen, 2006; Lundstrom, Gustafsson, & Unsbo, 2007), to gain deeper insights in the understanding of the visual system (Artal et al., 2004; Atchison, Guo, & Fisher, 2009; Atchison & Mathur, 2011; Ohlendorf, Tabernero, & Schaeffel, 2011) or to investigate how combinations of optical aberrations can be used to enhance visual perception (Applegate, Marsack, Ramos, & Sarver, 2003; de Gracia et al., 2010; Mon-Williams, Tresilian, Strang, Kochhar, & Wann, 1998). In particular, spherical defocus results in a rotational-symmetric blur circle in the retina plane and leads to a deterioration of the visual performance (Bradley, Thomas, Kalaher, & Hoerres, 1991; Charman, 1979; Jansonius & Kooijman, 1998; Sehlapelo & Oduntan, 2007). Although a change in the sign of the induced defocus would result physically in the same size of the blur circle, psychophysical measurements under polychromatic light conditions of human visual perception revealed an asymmetric reduction of visual acuity (Leube, Ohlendorf, & Wahl, 2016b; Radhakrishnan, Pardhan, Calver, & O'Leary, 2004b) and contrast sensitivity (Radhakrishnan, Pardhan, Calver, & O'Leary, 2004a), depending on the sign of the optically imposed defocus.

One explanation for the observed differences could be the interaction of the induced spherical defocus with inherent higher order aberrations, where the distribution of light at the paraxial plane is not

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symmetric anymore and acts as a directional cue for the visual system (Guirao & Williams, 2003). On the other hand, the chromaticity of visual stimuli together with the chromatic aberration of the human eye (Le Grand, 1964; Marcos, Burns, Moreno-Barriusop, & Navarro, 1999; Thibos, Bradley, Still, Zhang, & Howarth, 1990; Thibos, Ye, Zhang, & Bradley, 1992) was also discussed as a factor that allows the visual system to identify the sign of defocus (Ohlendorf & Schaeffel, 2009) and it was shown that this cue provides directional information for the accommodative system (Kruger, Nowbotsing, Aggarwala, & Mathews, 1995; Kruger & Pola, 1986; Lee, Stark, Cohen, & Kruger, 1999).

Therefore, the first hypothesis of the current study was that under monochromatic light conditions, the sign of an induced spherical defocus has no influence on the reduction of the visual acuity.

Next to induce blur by the use of defocusing lenses (*called observer method (Chan, Smith, & Jacobs, 1985)*), it is possible to deteriorate the displayed image itself by using Fourier optics and this is referred to the *source method* (Chan et al., 1985). Simulations of blur and the comparison to lens induced blur were shown to result in good agreement investigating astigmatism ($\Delta \log VA = 0.17 \pm 0.05$) (Dehnert, Bach, & Heinrich, 2011; Ohlendorf et al., 2011) and positive spherical defocus ($\Delta VA = 0.14 \pm 0.04 \log MAR$) (Dehnert et al., 2011).

The major difference between the observer and the source method is that the simulation (in case of the source method) results in a blurry image without inducing optical vergence at the same time. From accommodation theory it is known that blur perception is also driven by induced optical vergence (Fincham, 1951) and not blur alone (Del Águila-Carrasco et al., 2017; Esteve-Taboada et al., 2017; Kruger & Pola, 1986). Therefore, the second hypothesis was that a symmetric reduction of visual acuity occurs, when tested under a blur-only condition (source method).

In brief, the purpose of the current study was to investigate the sign-dependent subjective sensitivity to spherical blur in (1) monochromatic light conditions and (2) under blur-and-vergence and blur-only conditions.

2. Methods

To assess the visual performance under monochromatic light conditions, high contrast visual acuity was measured in two experimental blur conditions: 1) lens induced blur (observer method) and 2) simulated blur (source method) (Chan et al., 1985). Both blur conditions were designed with the same psychophysical setup and followed the same staircase procedure to measure the visual acuity.

2.1. Participants

A prospective, randomized study was carried out at the University Tuebingen enrolling 15 healthy participants (9 male and 6 female) with a mean age of 27.2 ± 3.4 years and a mean spherical equivalent refractive error of -2.98 ± 2.17 D (range from – 0.25 D to -6.00 D). Inclusion criteria for participation were a refractive error of less than – 0.25 D (range -0.25 D to -6.0 D), less than -2.00 D of astigmatism and best corrected visual acuity of 0.1 logMAR (6/7.5) or better. Participants with pre-existing ocular diseases were not allowed to take part in the study. All subjects were naïve to the purpose of the experiment. The study course was approved by the Ethics Commission of the Medical Faculty of the University of Tuebingen. The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all subjects after explaining the nature and possible consequences of the participation in the study.

2.2. Study protocol

All participants were screened for ocular health by an ophthalmologist. Thereafter, participant's pupils were dilated and physiologic accommodation was inhibited by the administration of a total of 3 drops of a cycloplegic agent (1% cyclopentolate hydrochloride; Alcon Ophthalmika GmbH, Austria) in participant's dominant eye, 1 drop at a time in 10 min intervals. Prior to the study, the objective refraction and the pupil size were measured with an aberrometer (ZEISS i.Profiler plus, Carl Zeiss Vision GmbH, Aalen, Germany). The subjective refractive error was assessed using a trial frame (UB4, Oculus, Germany) and trial lenses with an artificial pupil of 4 mm diameter under photopic conditions ($L = 250\ cd/m^2$). To control the emerged effect of the cycloplegic agent, push-up measurement (Chen & O'Leary, 1998) was performed before, in between and after the study measurements. Participants were given a training session prior to the visual acuity tests in order to familiarize them with the keypad and the staircase procedure. After the training, visual acuity was assessed under monochromatic conditions, using bandpass filters with central transmission wavelengths of 450 ± 2 nm (blue), 530 ± 2 nm (green) and 630 ± 2 nm (red) and a full half width maximum of 10 nm (Newport® Corporation). Luminance was set to $1\ cd/m^2$ in both methods (lens induced defocus or simulated defocus). To obtain the same luminous conditions for each filter, the luminance settings of the monitor were adjusted according to the specified transmission profile. Furthermore, spherical refractive errors were corrected for each filter separately, in order to account for changes in refraction due to chromatic aberration. The measurement sequences of the defocus level, the filter condition and the blur method (observer vs. source method) were completely randomized. All psychophysical measurements were performed with correction of refractive errors using a trial frame, on a distance between eye and display of 5.0 m and for a back-vertex-distance between trial frame and eye of 12 mm. The contrast of the stimulus was above 0.98.

To investigate the effect of the sign of defocus, the induced spherical defocus ranged from $+3.0$ D to -3.0 D in 1.0 D steps. In case the observer method was applied, the induced blur was produced by trial lenses placed in a trial frame and using an artificial pupil of 4 mm diameter. To simulate the blur in the displayed image (source method), a Fourier optics approach similar to the algorithm from Legras, Chateau, and Charman (2004) was used and participants pupil size was controlled by using a 4 mm artificial pupil. The image of the Landolt C was converted to the frequency domain using Fourier transformation and multiplied by the calculated optical transfer function (Thibos, Applegate, Schwiegerling, & Webb, 2002) of the defocus in regards to the given wavelength and pupil diameter. Visual acuity was tested for both blur conditions and each defocus level according to a BestPEST (Bach, 1996; Kingdom & Prins, 2010) adaptive staircase procedure incorporating 24 trials per threshold estimation, a fixed slope of the psychometric function of 2.0 and high-contrast Landolt C's as standard optotypes in eight possible directions (guessing rate of 0.125). The displayed image size was corrected for spectacle magnification using a distance between the lens and the principal plane of the eye of $h = 15$ mm (Benjamin, 2006; Chan et al., 1985). The visual acuity test was programmed in MATLAB (2016a, The MathWorks, Inc., Natick, USA) using the Palamedes toolbox (Kingdom & Prins, 2010) (Version: 1.8.2, 2016) and the Psychtoolbox (Kleiner et al., 2007) (Version: 3.0.13).

2.3. Analysis

To compare the reduction of visual acuity under different conditions, the slope of the regression line for visual acuity over defocus was analyzed. For the statistical analysis, repeated measurements analysis of variance was applied (IBM SPSS Statistics, IBM Corp., Armonk, NY), including the factors filter condition (blue, green and red), method (source and observer) and the sign of the induced defocus (positive and negative). Level of significance was set to $\alpha = 0.05$.

3. Results

3.1. Chromatic change of refraction and residual accommodation

The spherical refractive error of the participant's eye was adjusted for each filter condition separately to ensure that the best focus position