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Impact of Defocus in the Measurement of Light Distortion: Simulation and Experimental Measurements

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“Life is a series of experiences, each one of which make us bigger,

even though sometimes it is hard to realize this.

For the world was built to develop character, and we must learn

that the seatbacks and grieves which we endure help us

in our marching onward.”

- Henry Ford

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ABSTRACT

Currently it has been given more clinical relevance to visual disturbances that affect the performance of people in everyday activities, especially in low lighting conditions. In fact, vision quality is related with the resulting intraocular straylight from light scattering on optical means, the intrinsic aberrations of each subject and un-corrected refractive errors. All this can degrade the vision quality by perceiving dysphotopsias around light sources. There are several photic phenomena (like halos and starburst) associated to light distortion limiting the visual performance, especially in low luminance conditions, such as night driving. The association between intraocular light scattering and high-order aberration with visual quality and performance is well known and it is already taken into account in clinical practice for pathological situations, surgical and other visual treatments. It is known how defocus can influence the visual performance related to visual acuity, contrast sensitivity, reading and shapes and patterns recognition. However the increase on light distortion with defocus and its differences between myopes and hyperopes has not been yet studied. Therefore, it is relevant to study the impact of defocus in light distortion measures and how it is perceived, and any additional factors that may influence the visual quality along with the blur caused by non-corrected refractive errors as well, namely the action of accommodation, corneal surface regularity and symmetry and pupil size.

In this cross-sectional study involving 20 healthy subjects the size and irregularity of light distortion surrounding a bright source of light against a dark background were evaluated with the Light Distortion Analyzer (LDA) under low luminance levels with positive and negative induced defocus of 1.00D, before and after the instillation of a cycloplegic drug. From this study we observed that there was a relevant increase on light distortion with both types of defocus (positive and negative) and both types of induced defocus produced similar values of light distortion in size and irregularity. The spherical-like HOA was the ocular aberration that most influenced light distortion measures, mainly its size, but the pupil by itself did not show to have a significant influence. Besides, the topographic indexes SRI and SAI showed to be predictors of visual quality by being positively related with light distortion size. The same it was not verified for the simulated PSF with the psychophysical measure from LDA in both positive and negative induced defocus.

Given the results, we verified that despite the neural capacity of the binocular system to attenuate the monocular effects, the importance and need to correct low refractive errors should not be dismissed, not only for a matter of improvement of visual acuity but also visual quality under dim light conditions.

RESUMO

Atualmente a importância clínica dos distúrbios visuais que afetam a performance das pessoas em atividades do quotidiano, nomeadamente em condições de baixa iluminação, tem merecido relevo pela comunidade científica. De facto, a qualidade visual está relacionada com a dispersão da luz nos meios óticos, as aberrações oculares intrínsecas de cada sujeito e de erros refrativos não corrigidos. Tudo isto pode degradar a qualidade visual através da perceção distorcida de fenómenos luminosos (como halos e estrelas à volta das luzes) que limitam a performance visual dos sujeitos, nomeadamente em condições de baixa iluminação, como é o caso da condução noturna. A relação das aberrações oculares e da dispersão da luz intraocular com a qualidade e performance visual é já bem conhecida e tida em conta na prática clínica em situações patológicas, cirúrgicas e outros tratamentos. Sabe-se de que forma o desfocado pode influenciar a performance visual em termos de acuidade visual, sensibilidade ao contraste, velocidade de leitura, reconhecimento de formas e padrões. No entanto, não se conhece de que forma o desfocado aumenta a distorção luminosa e se difere ou não entre míopes e hipermétropes. Assim, torna-se relevante conhecer de que forma o desfocado tem impacto em medidas de distorção luminosa e como é percebida, bem como quais os fatores adicionais que poderão influenciar a qualidade visual juntamente com o desfocado provocado pela não correção de erros refrativos.

Neste estudo transversal utilizou-se o *Light Distortion Analyzer* (LDA) para medidas do tamanho e irregularidade da distorção luminosa em situações de baixa iluminação aquando da simulação de desfocado positivo e negativo de 1,00D, após a atuação de um fármaco cicloplégico. Este estudo mostrou haver um aumento relevante da distorção luminosa perante a presença dos dois tipos de desfocado, sendo que ambos desfocados hipermetrópico e miópico produziram valores semelhantes de distorção, tanto em tamanho como irregularidade. A aberração esférica de alta ordem foi a aberração que mais influenciou as medidas de distorção, mas a pupila por si só não mostrou ter influência. Além disso, os índices topográficos SRI e SAI mostraram ser preditores de qualidade ótica ao relacionarem-se positivamente com o tamanho da distorção. O mesmo não se verificou entre a simulação da PSF e a medida psicofísica do LDA para ambos os desfocados positivos e negativo.

Face aos resultados, verificamos que apesar da capacidade psicofísica do sistema binocular de atenuar os efeitos monoculares, não se deve descartar a importância e a necessidade de corrigir os baixos erros refrativos, não só por uma questão de melhoria da acuidade visual mas também de qualidade visual.

INDEX

ABBREVIATIONS AND ACRONYMS

BFCIrreg: Best fit circle irregularity

BFCIrregSD: Best fit circle irregularity standard deviation

BFCRad: Best fit circle radius

CSF: Contrast sensitivity function

ETDRS: Early Treatment of Diabetic Retinopathy Study

HCDVA: High contrast distance visual acuity

HOA: High Order Aberrations

IOLs: Intraocular lenses

LCDVA: Low contrast distance visual acuity

LCDVA+1D: Low contrast visual acuity with +1.00D of induced defocus

LCDVA-1D: Low contrast visual acuity with -1.00D of induced defocus

LDA: Light Distortion Analyzer

LDI: Light distortion index

LE: Left Eye

LOA: Low Order Aberrations

LogMAR: Units of measurement of visual acuity by the Logarithm of the Minimum Angle of Resolution

MTF: Modulation Transfer function

NTF: Retinal Brain function

p: Statistical significance

PSF: Point Spread function

Q: corneal asphericity value

RE: Right Eye

RMS: Root mean square

SAI: Surface Asymmetry Index

SD: Standard deviation

SRI: Surface Regularity Index

VA: Visual Acuity

INDEX OF FIGURES

INDEX OF TABLES

1. LITERATURE REVIEW

The human eye is a complex and imperfect optical system. Nowadays, the evaluation of visual quality goes beyond the measurement of visual acuity and the compensation of the refractive error. The image quality of the human eye is affected not only by the uncorrected refractive error and caused diffraction, but also by optical wavefront aberrations and light scattering that may produce a decrease on visual quality. Halos, *starburst* and scattering are some phenomena produced by the ocular wavefront aberrations, uncorrected refractive errors and other factors that degrade the optical eye quality when observing a bright light source, resulting on a distorted light image. The *Light Distortion Analyzer* (LDA) is a device that measures and quantifies the size and shape of this light distortion. In this literature review we will address topics and issues related to visual quality, since the characteristics of the retinal image quality, the factors that contribute for its degradation and how defocus may influence the light distortion and degrade de visual quality.

1.1 Characteristics of optical and retinal image quality of the human eye

1.1.1 Retinal Image Quality

The quality of the retinal image depends on the intraocular scattering, low- and high-order wavefront aberrations and uncorrected refractive errors. These phenomena are the main responsible for the degradation of optical quality and each one of them has its contribution on retinal image formation. [1-7] In this chapter it will be described which components are most important and have impact on the quality of the retinal image and which metrics are most used in order to classify them.

1.1.1.1 Ocular Scattering

Light scattering is a physical phenomenon in which light rays are deflected and deviated from the theoretical straight trajectory due to optical irregularities or non-homogeneities. These irregularities are characterized by variations on media's refractive index and the presence of small particles of different sizes and foreign bodies, inducing the combination of light diffraction, refraction and reflection. [1 8-10] Therefore, in the specific case of human optical system, ocular scattering is most usually due to changes on refractive index of the different structures of the eye (cornea, iris, sclera, crystalline lens, vitreous humor and retina). [1 3 10-21] Light scattering effect is also described as the angular distribution of the light intensity in the retina.[1 2]

There are two kinds of ocular scattering: the backward scatter, which is the amount of scattered light widespread out of the eye,[22] and the forward scatter, which is the light spread at low angles over the retina.[1 2] The backscattered light allows evaluating the quality of ocular tissues, so the most important component capable of compromise the retinal image by straylight is the forward intraocular scattering.[1 10 23 24]

Some authors suggest that the straylight in the retina increase with age in normal eyes due to transparency loss of ocular media, namely lens opacities. Straylight tend to double with the age compared to young healthy subjects. [3 10 11 19 23 25-27] Intraocular scattering affect the retinal image quality by decreasing the retinal image contrast when a bright light source is presented.[2] When the transparency of the ocular media and the organization of the histological structure are compromised, the intraocular scatter becomes more relevant, creating a decrease on retinal image contrast. Many ocular conditions can compromise the transparency and organization of the tissues, like corneal dystrophies, cataracts, vitreous changes, diabetic retinopathy and age-related macular degeneration.[3 10-19] So, in general terms, when any ocular condition decreases the transparency of the ocular tissues, it is accompanied by an increase in intraocular scattering and a consequent decrease of image contrast.[1 17]

1.1.1.2 Wavefront Aberrations

Such as scattering, wavefront aberrations change the trajectory of light rays propagation, but in a different way. The wavefront aberrations are defined as the wavefront deviation from a reference ideal optical system due to irregularities in the shape of optical surfaces. Aberrations can be described as chromatic – the defect occurs for different wavelength - and monochromatic - the defect only occurs for one wavelength.

The monochromatic aberrations are the type of aberrations that can cause the degradation of the retinal image by the straylight of a bright light source. On healthy eyes, where the transparency of ocular media is not compromised, the scattering quantity is almost irrelevant, which means that the ocular wavefront aberrations are the responsible for image degradation. These irregularities are mainly originated from cornea and crystalline lens, wherein the aberrations from crystalline lens compensates a proportion of aberrations from cornea.[3] Wavefront aberrations are described by mathematical expansion series named Zernike polynomials that extract the components of the wavefront error.[4 28-32] Zernike polynomials (or coefficients) are organized into a pyramid by different orders, with one or more terms in each order (**Figure 1.1**) represented by Z_n^m, where *n* is the order of the term and *m* is its frequency, and expressed in microns (µm). [28 32-34]The value of the total wavefront aberration is calculated by the root mean square (RMS) which is the square of the sum of the squares of each Zernike coefficient. The higher the coefficient value, the greater the impact on the total RMS wavefront error, leading to a decrease in the optical performance. [29 35]

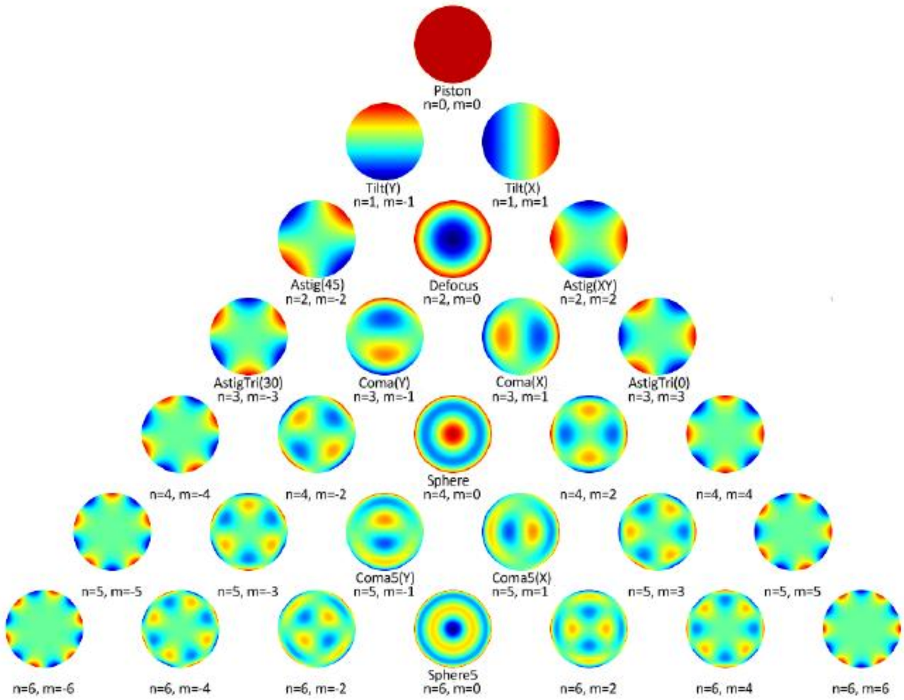


Figure 1.1 Zernike polynomials pyramid up to the 6th order with the correspondent order, frequency and name. Image reproduced from Specialistica, L. (2010).[36]

Aberrations are grouped into low- and high-order aberrations (LOA and HOA, respectively). LOA includes 0 to 2nd order Zernike terms and it refers to the tilts, prism and to the conventional refractive error (defocus and astigmatism). The 2nd order aberrations (defocus and astigmatism) are the main responsible for blurred retinal images and are the only ones that are routinely corrected with spectacles or soft contact lens.[37] Defocus and astigmatism are the most predominant wave aberrations accounting approximately 90% of the total wave aberrations of the normal eye.[38] Zernike terms from the 3rd order and above are included in the HOA group. Although HOA have a small contribution on the total eye's aberrations, their effect on image quality has been reported once their correction could significantly improve visual performance, particularly in eyes with corneal diseases, by ameliorating the retinal image quality. [4 39-43]

The amount and distribution of wave aberrations tend to be smaller with the increasing order and vary among the population. In general, the magnitude of HOAs tends to be around zero, except for 3rd order coma-like (horizontal trefoil, vertical and horizontal coma and oblique trefoil) and 4th order spherical aberrations.[7 33 38 44] In normal eyes, spherical (Z_4^0) and 3rd order coma aberrations tend to be slightly positive and oblique trefoil (Z_3^3) tend to take negative values. Even if their magnitudes are low, these aberrations have a negative influence on retinal image quality and in healthy eyes they may be the most responsible for night vision complaints.

Figure 1.2 illustrates how these three aberrations can distort individually an image. The total magnitude of coma and spherical aberrations are the result from the magnitude of these aberrations on the cornea that the crystalline lens does not offset. [3 7 44-47]

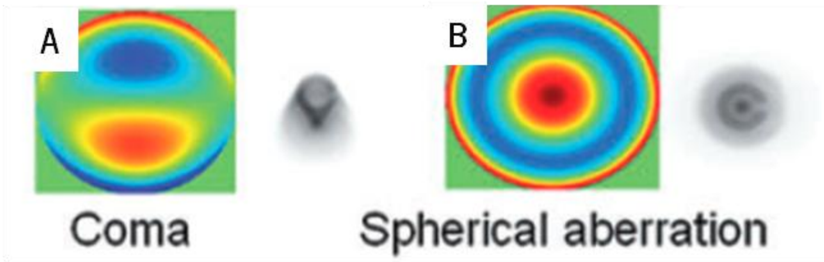


Figure 1.2 Simulation of an image distorted by coma-like (A) and spherical-like (B) HOA. Image reproduced from Maeda (2009). [30]

Of all the HOAs, the wavefront aberration that clinicians give more attention is the spherical aberration. This is because in normal healthy eyes the spherical-like HOA tends to be more positive values and with a major magnitude than the other HOA and because increases with the pupil dilatation. [7] Total Spherical-like HOA normal RMS was found to be approximately 0,15μm for a 6mm pupil diameter in subjects between 20 and 29 years old. [48]

Many factors can induce changes in normal wavefront aberrations including ageing [30 48 49], accommodation [50 51], changes in tear-film volume and dynamics [52], contact lens [53], corneal pathologies [54 55], surgical and non-surgical corneal treatments [56 57] and cataracts. [30 58] This issue it will be addressed in subsection 1.2.1., as the relationship between refractive error/defocus and wavefront aberrations in subsection 1.3.2..

1.1.2 Metrics and Methods for Evaluating the Visual Quality

As referred before, intraocular forward scattering, eye aberrations and diffraction are the responsible for the imperfection of the optical system. When evaluating the quality of vision by analyzing the effect of scattering and wavefront aberrations, there are several metrics/parameters that allow us to get a sense of how the retinal image is affected; for example, an aberrated eye produces a more extended and asymmetric retinal image. The most common metrics used to estimate the deterioration on image quality beyond the RMS are the point-spread function (PSF), the modulation transfer function (MTF) and the Strehl ratio (SR).

The PSF is the light distribution of a point object at the retinal image and it is limited by the straylight/intraocular forward scattering and by the wavefront aberrations of the eye at the exit pupil. [1-3 16 59-61] This parameter defines the way a certain amount of light is redistributed and how it looks after passes through an optical system.[62] In practical terms, the PSF corresponds to the light distribution surrounding a bright spot light when seen against a dark background. [63] Its outer part, which goes beyond 1° of its distribution, is called straylight and it is the cause of disability glare and other visual complaints.[1 16] While the external contour of the PSF corresponds to the scattering effect – straylight -, which strongly declines with the increasing angle, the central area is mainly affected by ocular aberrations. [1 63] The effect of aberrations on PSF is based on the magnification of the straylight and reduction in contrast of the retinal image. Each wavefront aberration can be represented by its own PSF [60 62]: for example, **Figure 1.3** illustrates the PSF of optical effect induced by Z_4^0 aberration. Some studies show that PSF influence the patients' night visual complaints and is a reliable method for their validation.[62 63] The MTF and the Strehl ratio are derived from the PSF and provide quantitative data to evaluate the impact of aberrations in visual quality.

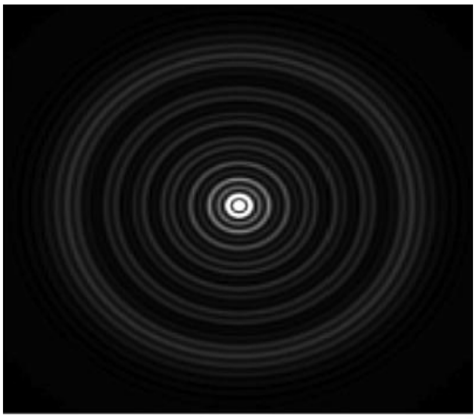


Figure 1.3 Simulation of a PSF obtained by the effect of spherical-like HOA. Image reproduced from Mello et al. (2012).[60]

The MTF is an optical metric of image quality for grating objects representing contrast information of an image.[62] This function describes the variation of image contrast with the spatial frequency by measuring the contrast losses produced by an aberrated optical system.[1 3 33 59-62] The MTF differs with grating orientations and its values may vary from 0 to 1, where 1 indicates that the image contrast was 100% maintained from the object and describes an eye without any imperfection in the optical system– a perfect ideal eye – and 0 means that the image contrast was completely degraded so that the grating cannot be distinguished.[33 62] So, the lower the MTF values, the lower the contrast of the image and the poorer the retinal image quality. Once MFT is directly related to the decreasing contrast with the increasing spatial frequency, it is usual to associate it with the contrast sensitivity function (CSF) which represents a psychophysical measure of the contrast perception as a function of spatial frequency. These two metrics, MTF and CSF, are associated with NTF (retinal brain function) so that CSF depends on MTF and NTF. For example, after an ocular surgery, if there were not changes in NTF, the functional vision (CSF) will be proportional to the optical quality (MTF). Marcos et al. (2001)[64] found that a decrease in MTF was accompanied by a decrease in CSF in post-LASIK myopic patients. However, if MTF do not suffer changes, any improvements on CSF will be proportional to increases on NTF by neural adaptation.[65] Because of this proximity between the two metrics (MTF and CSF), the MTF can be obtained by the direct measuring of the CSF with sinusoidal fringes as the ratio between the conventional CSF and the interferometrical CSF - this was how the MTF was early obtained.[3]

Although the Strehl ratio (SR) metric is useful to describe the PSF of an eye[33], it can be also obtained from MTF. The SR is defined as the ratio between the actual peak intensity of an eye's PSF with aberrations and the peak intensity of a diffraction-limited (aberration-free) PSF, or equivalent, as the ratio between the volume of the actual MTF and the volume of a diffraction-limited MTF. This comparison is also taken for the same pupil size.[1-3 33 59-62] Its values range from 0 to 1, wherein 1 corresponds to a perfect optical aberration-free system.[33 60] This means that the higher the values of the Strehl ratio, the lower the values of RMS and the better the retinal image quality. It is usually considered a SR higher than 0.8 for a diffraction-limited system [3 33 61] and for lower levels of SR the extent and shape of the external contour of the PSF becomes more important than its peak value degrading the image quality.[59]

Different methodologies have been proposed and described in order to quantify the retinal image quality through the visual quality metrics described above, but only a few were approved and validated. The procedures could be from psychophysical to optical approaches. In optical methods, the Double-pass (DP) system and the Hartmann-Shack Wavefront Sensor (HSWS) are the methods used to objectively quantify the visual performance by ocular scattering and wavefront aberrations. The devices may be based in one of them or in both together. The DP system records the retinal image after a beam double-pass through the ocular media and reflects on the retina. The DP system provides information about the PSF, its external contour and limited to small angles, and the MTF can be calculated from the images obtained.[1 3] Relative to HSWS, this optical method is mostly used to measure the ocular aberrations and provide their Zernike polynomials magnitude but can also provide information about the MTF. [60 66 67] However, the MTF obtained by the DP system overcomes the one obtained by the HSWS system because the DP system is more sensible to the scatter than the HSWS one, producing a more accurate description of the optical quality.[1 7 68] The Compensation Comparison method is the most relevant psychophysical procedure to measure the intraocular forward scattering and it is the basis of the development of a commercially available device, the C-Quant. This psychophysical procedure is a 2-alternative forced-choice method in which the subject should compare and equalize the two stimulus presented in the two halves of a central ring while a flickering stimuli (that use glare) is presented in a peripheral ring. The results are provided in a psychometric curve for the magnitude of forward scattering in log units, [1 23 69] so the higher the logarithm of scattering, the higher the intraocular forward scattering.[1 70 71]

Like ocular scattering and wavefront aberrations, the PSF, MTF and Strehl ratio can suffer changes due to media's transparency loss and changes in the structure of the ocular elements. There are several studies founding changes in these visual quality metrics, proving the affectation of vision (see subsection 1.2.1).

1.1.3 Influence of Luminance and Pupil Size

The human eye is a complex optical system and relies on the optical quality and transparency of its components. Besides the ocular scattering, eye aberrations and diffraction the quality of vision also depends on the luminance of the background and on the pupil's aperture.

Luminance is a photometric measure that describes the amount of light passing through a defined area and reaches a particular solid angle by measuring the luminous intensity per unit area of light in a given direction. Its International System unit is candela per square meter (cd/m^2). [72] In the optics domain, the luminance conditions of a specific scene can be classified in photopic (10 to 10^8 cd/m^2), mesopic (10^{-3} to $10^{0.5}$ cd/m^2) or scotopic (10^{-6} to 10^{-3} cd/m^2) luminance levels. [72 73]

It is well known the relationship between the luminance and the pupil diameter. The iris muscle controls the pupil size in order to control the amount of light entering the eye.[38] So, for higher amounts of luminance (photopic levels) the iris muscle constricts decreasing the pupil aperture, leading to a minor amount of light reaching the retina. The opposite happens to the pupil diameter when the luminance decreases. In these terms, pupil size and luminance are always related and they should have been taken into account in every clinical and experimental situation.

Usually in the routine clinical examination the visual acuity is only measured under optimal conditions, which means a high luminance background and contrast targets. However, under mesopic and scotopic conditions the visual acuity tends to be worse than that on optimal visual conditions. [74-76] Johnson & Casson (1995) [76] found that the LogMAR visual acuity increases linearly as the logarithmic luminance decreases, which means that the visual acuity decrease with the decreasing luminance. Besides, they also found that when contrast and luminance are reduced the visual acuity is degraded by a greater amount than that produced by only one of these factors alone and that when there are a few factors influencing the visual acuity they appear to have an additive influence. However, Simpson et al. (1986)[77] found that with low luminance levels the effect of blur on visual acuity is lower than with high luminance levels.

The visual performance it is also dependent on the Stiles-Crawford effect (SCE) – phenomena where the light passing through the edge of the pupil does not appear as bright as light passing through its centre (Stiles & Crawford, 1933) [78]. This effect reduces the effective retinal luminance but, as suggested by many authors [79-81], it can improve spatial vision with large pupils by attenuating the influence of defocus and aberrations on vision.

The pupil diameter considered to provide the best resolution is around 3mm because it is the pupil size which balances the contribution of the HOA and diffraction producing a minor degraded image. However, this depends on subject's wavefront aberrations distribution and on the wavelength. Several studies shows that the retinal image quality decreases most often under scotopic or mesopic conditions when the pupil reaches its maximum diameter. [48 76 82-85] As the pupil size increases so does the ocular aberrations (**Figure 1.4**) and the external contour of the PSF (**Figure 1.5**) reducing the retinal image quality by the increased blurring effect. The opposite happens with the Strehl ratio that becomes lower as the pupil becomes bigger. [60 86] Spherical-like HOA (4th and 6th order) are among those that degrade the image quality in a more significant manner as the pupil dilates. Therefore, they become increasingly important at low luminance levels which is particularly important in subjects who underwent refractive surgeries.[85 87]

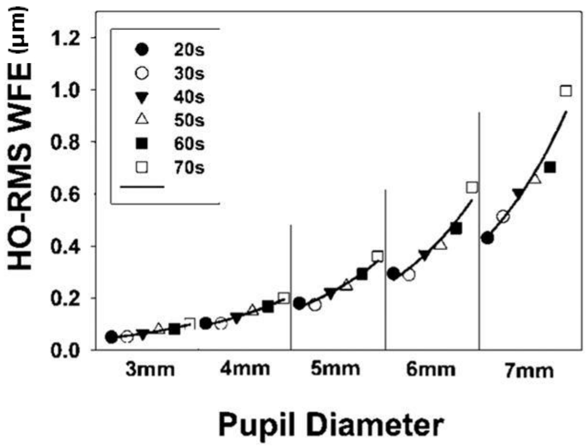


Figure 1.4 Changes in Total HOA RMS magnitude as function of age for different pupil diameters fitted with an exponential function. Image reproduced from Applegate et al. (2007). [48]

Nevertheless it cannot be admitted that the image quality is better for smaller pupils. For a pupil size below 3mm the image quality is less influenced by aberrations due to the diffraction effect which predominate above aberrations. Decreasing the pupil diameter can also degrade the image quality by restriction of the amount of available light although it allow the depth of focus to increase.[2 3 7 38 60 87] On **Figure 1.5** are represented the changes in PSF with the pupil diameter of an aberrated eye, demonstrating how diffraction and HOAs can distort a light spot.

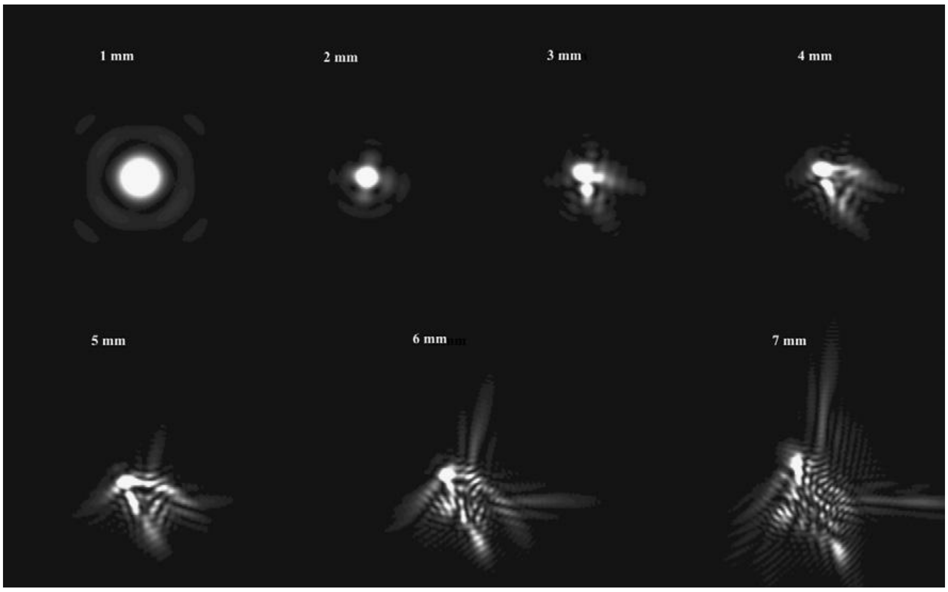


Figure 1.5 PSF as function of pupil diameter in an aberrated eye. As the pupil increase the higher the effect of HOA in PSF, but for smaller pupils the effect of diffraction increases. Image reproduced from Mello et al. (2012). [60]

1.2 Light Distortion and Night Visual Disturbances

Nowadays the number of people going to an ophthalmology/optometry appointment with complaints of how the light of the cars bothers them when driving at night have been grown. These complaints are not only perceived by normal healthy subjects, but almost for the entire population, especially those who undergone ocular surgeries, have transparency loss, uncorrected refractive errors and others. According to Jabbur et. al (2004) [88] the most subjective complaints of dissatisfied patients after a refractive surgery were blurred distance vision (59.0%), glare and night vision disturbances (43.5%). In fact, the image quality degradation is due to the summation of intraocular scattering, ocular aberrations and uncorrected refractive errors. In healthy eyes these factors reduce the image quality due to the distorted light reaching the retina, leading to a perceived blurred and distorted image and glare. This happens mainly at night when pupil is physiologically dilated and when images are viewed against a dark background. In this section it will be described the photic phenomena causing light distortion related to subjects complaints at night and the factors causing the disturbances, as well as the most recent methods of evaluating the light distortion.

1.2.1 Photic phenomena (starburst, halos and glare)

Many people complaints about poor night vision due to photic phenomena caused by light distortion. The photic phenomena of light distortion described in literature are glare, starburst, haloes, hazy vision, monocular diplopia and polyopia and defocus. [62 87-96] These phenomena are also known as dysphotopsias. Jabbur and his co-workers (2004) [88] reviewed the complications of dissatisfied patients who undergone refractive surgery and they found that the most common complaints were blurred vision, glare and night vision problems, such as halos, multiple images and hazy vision.

To better understand these complaints there is a need of defining the terms. Images from the QoV [91] are used to exemplify each photic phenomenon.

In general, glare (**Figure 1.6A**) refers to a light source appearing bright and intense and it is caused by scattered rays in light path from media opacities.[92 97] Glare phenomena can be divided into discomfort glare and disability glare.[15 25 87] The first one is a subjective discomfort sensation induced by a bright light source without causing significant losses in visual performance [15 25] while disability glare is associated to a functional impairment affecting the retinal image contrast.[23 25 26 87]

Halos (**Figure 1.6B**) and Starburst (**Figure 1.6C**) are night visual disturbances phenomena that degrade the size and shape of a light source. Halos are among the most reported phenomena next to glare and can occur with or without starburst. This light disturbance is perceived as circular shadow surrounding a light source and it is caused by refractive phenomena. Usually they are assumed to be a consequence of the contribution of the spherical high-order aberration, especially when in refractive surgeries the treated optical area is smaller than the pupil diameter in mesopic and scotopic conditions.[87 93] Starburst is a radial or regular radiating scatter of light from a point source affecting its size and regularity. This phenomenon might be explained by the diffraction of light at the crystalline lens suture lines formed by the union of their fibers. [98] It is commonly described as a star image for almost every people, even the ones who wear glasses and contact lens, especially when they are under-corrected or not corrected at all.[87 92 93]

Other photic phenomena are hazy vision (**Figure 1.6D**) and blurred or defocused vision (**Figure 1.6E**) and they are usually confused. Hazy vision is usually caused by loss of transparency of the ocular media and it is defined by a reduced visibility with contrast losses. Patients used to report complaints of foggy vision such as when looking through a foggy window. Defocused vision is caused by an uncorrected refractive error and the limits of images sharps seem to not be clearly.

Monocular diplopia and polyopia (**Figure 1.6F**) are normally associated to ocular diseases but in this case can be a consequence of light distortion. Also known as ghosting, this phenomenon is perceived as a partial troubled faint or a double/multiple images that overlap.[92]

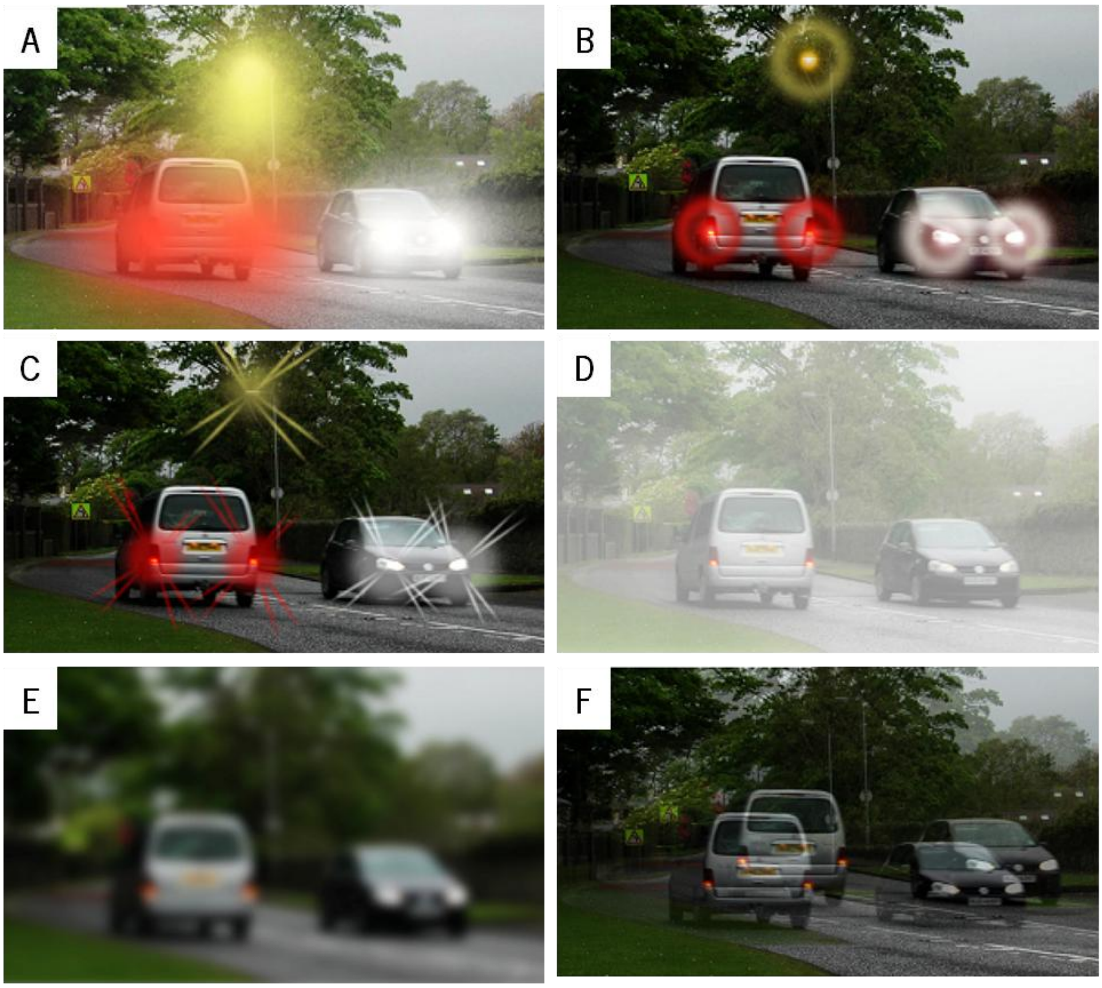


Figure 1.6 Pictures from the Quality of Vision (QoV) questionnaire of the night visual symptoms and photic phenomena. Image reproduced from McAlinden et al. (2010). [91]

All the described night vision disturbances are mainly reported by people with ocular pathologies, corneal changes and subjects submitted to refractive treatments (surgical and non-surgical) – see subsection 1.2.2 - but can also be reported from subjects with uncorrected refractive errors (section 1.3) or even well corrected patients.

1.2.2 Disturbing factors and complaints

In healthy young subjects, the night visual complaints are due to the magnitude of the intrinsic ocular aberrations of each subject. The night visual complaints have implications on quality of life and in many living activities. Driving at night is one of the living activities which performance can be diminished due to the visual disturbances caused by light distortion. [15 25 74 75 89 99-103]

Whenever there is a change in the optical components of the eye, the quality of the image on the retina can be changed and usually reduced. As seen in anterior sections the transparency loss of the optical components of the eye, ocular aberrations and changes in the refractive index of the different ocular components can alter the light path by dispersion and scattering, culminating into light distortion perception. Having this into account, whenever there is an ocular pathology changing the media transparency or the propagation of light rays, the light reaching the retina will be distorted and the retinal image will not be clearly perceived.

There are many studies that evaluate the image quality changes due to different pathologies, conducting to a light distortion. There are many studies relating changes in intraocular straylight and wavefront aberrations due to ocular pathologies, such as cataract [11 15 19 23 25 70 99 104 105], age-related macular degeneration [86 106], keratitis [86 106 107] and keratoconus [3 12 17 23]. In these studies it is reported an increase in intraocular scattering due to the changes in media transparency or due to changes in ocular aberrations resulting from corneal changes. In general they found a decreased in contrast sensitivity at almost all the frequencies tested, a decreased MTF, lower values of Strehl ratio, less intense and more spread PSF and a higher light distortion disturbance perceived by subjects affected with the mentioned conditions. So, at some point the straylight and light distortion evaluation can be an important method to assess and classify the severity level of the pathological conditions. [10 12 15 30 60 97 105 108]

Other interesting factor affecting straylight, and by consequence increase light distortion, is the wear of contact lens due to the induced edema. Elliot et al (1993)[109] found about 50% of increased straylight induced by 10% of corneal swelling related with hydrophilic contact lens wear. However, the straylight values decline linearly with time as the corneal swelling decreased after contact lens removal. [53 60 109]

Not only pathologies alter the media's transparency and the refractive index. Nowadays, refractive surgeries have a great impact on visual quality due to the changes in the ocular wavefront aberrations. There are many reports of night visual disturbances complaints among subjects that undergone a refractive surgery with LASIK [56 62 71 84 85 87 88 93-95 97 101 110-115] and PRK [116 117]. Among others, Ortokeratology is a refractive non-surgical treatment that also changes the ocular aberrations and increases the light distortion.[85 115 118-120] All these refractive treatments were found to increase the light distortion due to an increase in high order ocular aberrations, especially in 4th order spherical aberration, which in myopic ablation it is positively induced.[121] This consequently increases the halo size compared with the halo without any invasive refractive treatment. In these refractive treatments the haloes complaints are usually associated to a larger pupil diameter compared with the optical treatment zone.[84 87 94 110] However, some authors do not consider that the pupil size is a predictor of the night visual complaints.[95 111 112 114] Once again most of the studies about the increase on night visual complaints and light distortion also report decreases on contrast sensitivity MTF and Strehl ratio, such as in pathologic conditions. Reinstein et al. (2012)[122], Schallhorn et al. (2009)[101] and Oshika et al. (2006)[56] found that the subjects undergoing LASIK with wavefront-guided technique had less night visual complaints than subjects submitted to conventional LASIK. Other common refractive treatment that could cause night visual disturbances complaints are the implantation of intraocular lens. [101 123-131] This is especially important for multifocal and diffractive lenses implantation for presbyopia correction. While some authors [126 127] found the performance with refractive multifocal IOLs to be comparable with monofocal IOLs, Brito and his coworkers (2015) [129] found an increased light disturbance although the good functional visual performance with diffractive multifocal IOLs. Besides Vega et al. (2015) [125] found differences in optical quality, through-focus performance and halo of four diffractive multifocal IOLs.

Castro et al. (2014) [82] evaluated the influence of alcohol consumption on the retinal image quality and night vision performance under conditions of low illumination. They found that the alcohol levels deteriorated the retinal image quality and the visual performance at night, being the deterioration positively associated with high alcohol levels consumption.

The influence of refractive errors on light distortion will be discussed on section 1.3.

In summary, besides diffraction, light distortion also depends on the summation effect of intraocular scattering and high order aberrations. As seen above, in cataractous eyes the intraocular scattering is more relevant on light distortion and night visual complaints than the ocular aberrations, but when the corneal optical integrity is altered the ocular aberrations are the main responsible for the night visual disturbances.

1.2.3 Methods of evaluating Light Distortion

Nowadays, light distortion is currently taken into account on a clinical examination. In order to assess how patients perceived a bright light spot in low luminance levels and to understand how their quality of vision are affected by scattering, high-order aberrations and other factors, many researches created different methods of evaluating the visual performance and light degradation. In this study we will only refer the ones seems more relevant and more used in the scientific community.

There are psychophysical and optical methods to measure and quantify the straylight. In psychophysical procedures the evaluation depends on the subject's response and performance while in optical procedures this is not an issue. However, the psychophysical procedures allows to have more meaningful results because translate the actual visual function of the subjects and the optical procedure have the disadvantage of being limited in the angular domain, which make it less functional.[1]

The optical methods most commonly used are the Optical Quality Analysis System (OQAS™, Visiometrics S.L., Terrassa) and Hartmann-Shack Wavefront sensor. The OQAS is based on a double-pass system for the analysis of the PSF of the retinal image and is capable of calculating the MTF, always considering the scattered light and the high-order aberrations.[1 18 19 70 86 106 132] Hartmann-Shack sensor is most commonly used to measure the ocular aberrations in a single direction, not being sensitive to the dispersed light and underestimating the visual quality in high glare situations.[1 67 68]

One of the most frequent psychophysical methods for the measurement of straylight is the compensation comparison method – the C-Quant Straylight Meter (Oculus Optikgeräte GmbH, Wetzlar-Dutenhofen, Germany). In this method the subject has to compare two central stimuli flickering in counter-phase and decide which flickers more strongly, while a peripheral flickering stimulus is presented in order to induce scattering. This is a two-alternative forced-choice method so the subject has to answer even when do not perceive differences.[1 17 23 26 63 71 105 111 133 134] Other psychophysical methods of evaluating light distortion are based on a central high-luminance stimulus inducing glare over a dark background and the subject has to detect a luminous peripheral stimulus around the central one. The instruments are Halo v1.0 software (Laboratory of Vision Sciences and Applications, University of Granada, Spain) [82 96 102], Starlights system (Novosalud, Valencia, Spain)[94 114] and Light Distortion Analyzer (LDA, CEORLab, University of Minho, Braga, Portugal)[119 129 135 136]. The difference between LDA and the other two instruments (Halo v1.0 and Starlights) is that LDA allows "to measure the light distortion under more realistic conditions using hardware with physical LEDs"[136] while the Halo v1.0 and Starlights use a computer screen display with projected light spots for the generation of glare and peripheral stimuli.[82 94 96 102 114] For that reason in this study we will use the Light Distortion Analyzer to evaluate and quantify the size and irregularity of light distortion. The instrument will be described in section 3.3.6.

There are many other instruments referred in the literature to quantify light distortion, or straylight, and evaluating how it degrades the retinal image with psychophysical and optical principles.[15 87 97 105 108 127 128 137 138]

Apart from these, McAlinden and its coworkers (2010) [91] developed a different way of measure the subjective quality vision by an inquiry. They called him Quality of Vision (QoV) questionnaire. The QoV Questionnaire consists on a Rasch-model test linearly scaled with ten items with three questions each, providing a quality of vision score for symptoms' frequency, severity and bothersome, resulting in a questionnaire with thirty item in total.[91] This questionnaire is already validated and requires an authorization of the corresponding author to calculate the score.

1.3 Impact of defocus on visual quality

Uncorrected refractive errors are one of the leading causes of visual impairment, in a significant proportion of the general population, even in developed countries, either if they are undiagnosed or inadequately corrected. [139-143] These refractive errors generate blurred/defocused retinal images, reducing the contrast of the images and inflict a lower limit to visual perception. [2 5 74] The defocus produced by the non-correction of the refractive errors reduces the visual performance of young and elder people on almost every visual task. Many studies [74 75 100] shows that the induced defocus have a detrimental impact on driving performance, especially at night. Cohen and coworkers (2007)[103] investigated the relationship between night myopia and the number of driving accidents in a group of professional drivers and they found that when subjects presented night myopia over 0.75D they are more likely to be involved in driving accidents at night. Certain levels of blurred vision can also influence the athletic and reading performances.[144 145]

1.3.1 Defocus and wavefront aberrations

In section 1.1.1.2 the conventional refractive errors (defocus and astigmatism) were already classified as being part of the low-order ocular aberrations. These 2nd order aberrations are considered the most prevalent aberration of the human eye, being predominant over the high-order aberrations, and they are the only ocular aberrations that can be neutralized by ophthalmic correction. However, even when the eye is free of refractive error the produced retinal image it is not perfect because of the small contribution of HOA [2], especially at mesopic and scotopic conditions, as seen previously. Usually, a total HOA RMS of 0.25μm for a 5mm pupil is approximately equivalent to a defocus of 0.25D in young healthy eyes.[2] Both defocus induced by uncorrected refractive errors and HOA decrease the visual acuity and the contrast sensitivity.[7 111]

Cheng et al. (2003)[47] found no correlation between HOA and myopic and hyperopic refractive errors. Additionally they did not found differences between the magnitude of spherical-like HOA from the ametropic eyes and from the emmetropic ones. The same was verified by Rossi and his coworker (2007)[37] between emmetropes and low myopes, and by Kingston et al. (2013)[46] in individual with similar ages from different continents. Many other authors [7 40 46 59 60 146 147] refer the existence of an interaction between LOA and HOA, mainly between the ametropia or defocus and the spherical-like HOA. Guirao et al. (2003)[59] explored the impact of HOA on subjective refraction and they concluded that HOA influence the amount of spherical and cylindrical refraction required for correction once the mean absolute error in spherical equivalent increased with the increase on HOA.

Several studies evaluated HOA as function of myopic refractive error, showing a tendency for a worsened visual quality in higher myopia degrees.[3 7 148 149] Marcos et al. (2000) [149] observed an increasing in corneal and internal HOA but a non significant change in total HOA with myopia. The positive increase in corneal spherical-like HOA is associated to a positive increase in corneal asphericity with myopia but this is usually compensated by the internal spherical-like HOA which increase in the opposite direction. However, they thought that the main responsible for the degradation in visual quality in myopia would be an increase in coma-like and other HOA. A study from Llorente et al. (2004) [146] compared the ocular aberrations between two groups of hyperopic and myopic eyes matched in age and absolute refractive error and they found higher positive amounts of total spherical-like HOA in the hyperopic group. Besides Thibos et al. (2002) [147] found a moderate positive correlation between defocus and spherical aberration in subjects between 22 and 35 years old with corrected refractive errors and paralyzed accommodation. So, in general terms, these studies demonstrate that the interaction and contribution of the spherical-like HOA with the defocus (spherical refraction) should be taking into account.

In addition to these findings, the influence of pupil size should not be forgotten, especially at low luminance conditions. Even for a fixed pupil size the blurred retinal image can be expanded by the increasing defocus caused by ametropia. The same happen when ametropia does not change but the pupil size increase, which magnifies HOA expression, mainly spherical-like aberration. In this context, some authors [35 37 40 60] believe that the adaptive optics correction of HOA can improve the visual quality due to a shift in subjective best focus of the image.

1.3.2 Impact of defocus in Visual Acuity and contrast sensitivity

The relationship between defocus and the loss of visual acuity it is studied since very early. Both spherical and astigmatic refractive errors affect the visual acuity. A defocus of 0.25D (negative or positive) may not have a great impact on visual acuity but for larger values of spherical or cylindrical defocus, VA tends to drop quickly. [2]

Many studies report losses of visual acuity due to the presence of defocus. [76 104 145 150-154] In order to study the additive influence of luminance, contrast and blur on visual acuity, Johnson and his coworkers (1995) [76] found a reduction at about 0.40 LogMAR units in VA with a induced blur of +1.00D on the best distance correction for a 97% contrast letters in subjects between 26-43 years old. Besides, they found that the VA decline was more abrupt for levels of blur up to +2.00D, being more gradually decreased for dioptric blur greater than +2.00D. They also found a significant reduction in contrast with the increasing positive defocus and reported that "low contrast targets appear to be more greatly affected by small amounts of blur than are high contrast targets". Wood et al. (2008) [104] reported a 0.28±0.05 LogMAR VA decrease and a significant reduction in contrast sensitivity induced by a certain non-described quantity of positive induced blur.

Figure 1.7 shows LogMAR visual acuity as function of induced defocus two pupil diameter obtained by Villegas et al. (2002) [150] with the accommodation paralyzed. Both curves show that the VA decreased with both negative and positive defocus but the VA loss is higher with the positive defocus (at about a 6/9 loss). The same is seen on defocus curves obtained by Sheppard and his coworkers (2013) [124]. However, it is important to have in account that besides defocus and the magnitude of HOA, the level of luminance and the pupil size can also influence VA and contrast sensitivity values. When in low luminance levels and/or low contrast, the VA tends to worse in a major magnitude than in optimal luminance and contrast levels. [2 76 104 155]

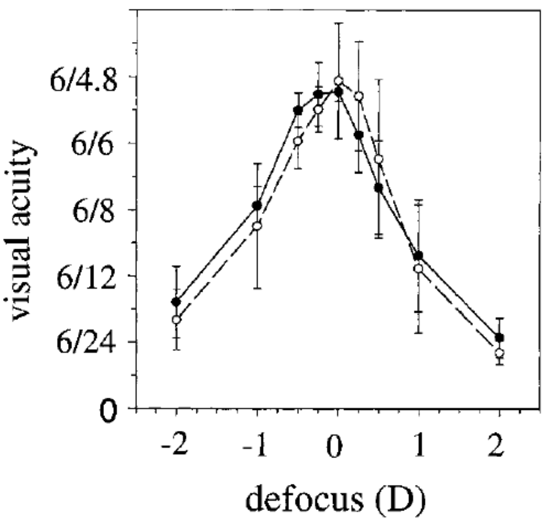


Figure 1.7 Visual acuity as function of defocus for 3mm (black circles) and 5mm (white circles) pupil diameter with cycloplegia. Image reproduced from Villegas et al. (2002). [150]

Other aspect to have in account is the blur adaptation. Some studies [153 155] reported that the visual performance after a period of blur adaptation can be improved by changes in visual acuity and contrast sensitivity. These studies observed an improvement in VA and contrast sensitivity after a period of blur exposure and showed that myopes are more tolerant to retinal defocus compared to emmetropes. This tolerance can be explained by their daily experience with blurred images.

1.3.3 Impact of Defocus on light distortion

There are not many reports of what are the normal values of light distortion in a healthy subject. Puell et al. (2013)[156] developed a study in order to determine the normal halo size in 147 healthy subjects in a large ages range (20 to 77 years) and to evaluate the repeatability of the Vision Monitor (MonCv3; Metrovision, Pérenchies, France). They found the normal halo size to be 36.5±28.8mm, considering a wide range of age.

As the ocular aberration and intraocular scattering, the uncorrected refractive errors can distort the retinal image which produces a decrease on visual acuity and contrast sensitivity and, at mesopic and scotopic conditions, can origin night visual disturbances produced by the distorted light reaching the retina. So, at night, the combination of HOA, intraocular scattering and defocus produced by uncorrected refractive errors decrease the visual quality and performance due to light distortion, producing the perception of photic phenomena in the presence of a bright light source. It is known how HOA increase the perceived size and shape of a light source by itself, especially the spherical-like aberration, and that defocus from uncorrected refractive error also produce higher values of light distortion. However, there are not many studies evaluating the differences between positive and negative defocus on light distortion.

Gutierrez and his co-workers (2003) [96] developed a system (Starlights halometer (Novosalud, Valencia Spain)) to quantify the presence of halos in subjects and their results did not show differences between emmetropic and ametropic with positive and negative refractive status in light distortion. Besides, Villa et al. (2007) [94] evaluated the disturbance index with the same referred device and they found an increase on this index correlated with corneal HOA only. However, Villegas et al. (2002) [150] studied the existence of a correlation between optical and psychophysical parameters as a function of defocus and found that the double-pass retinal image increased with both positive and negative induced defocus (**Figure 1.8**). But, as seen in **Figure 1.8** there are quite small differences between the disturbances on double-pass retinal image obtained by positive and negative defocus, although the Strehl ratio between both types of defocus was not significantly different.

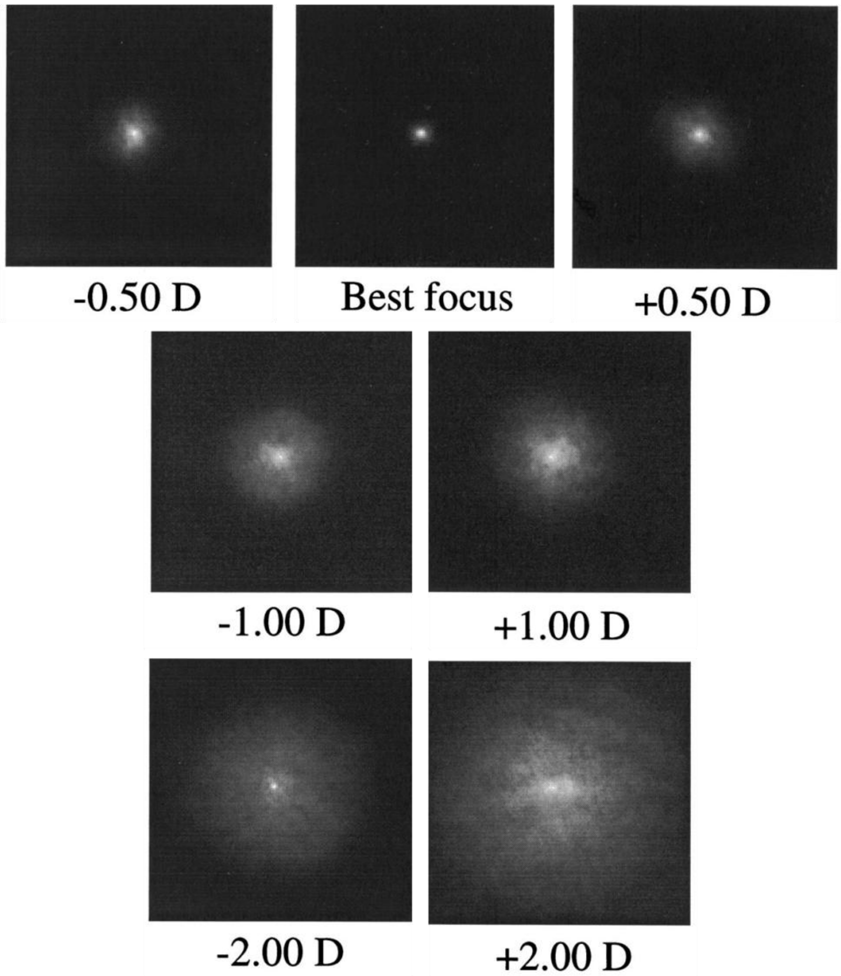


Figure 1.8 Double-pass images (PSF) for different types and levels of defocus obtained with a 3mm pupil. Image reproduced from Villegas et al. (2002). [150]

Artal et al. (2011) [70] used the OQAS system to assess the given objective scatter index (OSI) and they referred that this parameter can be affected by uncorrected refractive errors besides HOA. They showed that the OSI values significantly increase for values over +1.00D of defocus. A pilot study conducted in Portugal by Amorim-de-Sousa et al. (2014) [157] evaluated the variation on monocular light distortion with the increasing positive spherical and astigmatic defocus with the LDA (described in section 1.2.3). They access to a size index of light distortion size (LDI) and they found an increase with the increasing induced spherical and astigmatic defocus, being more significant over +1.00D for the spherical defocus, included (**Figure 1.9**).

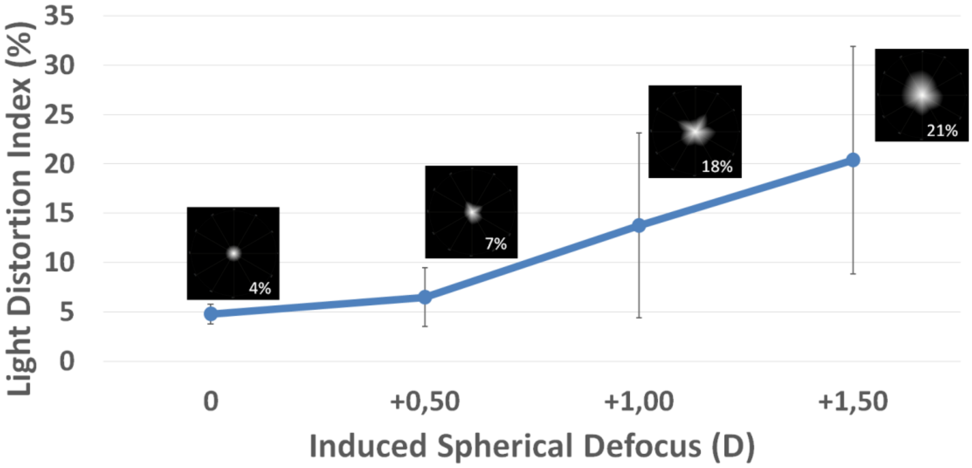


Figure 1.9 Changes in LDI, a size parameter of light distortion from LDA, with positive induced defocus without cycloplegia. Image reproduced from Amorim-de-Sousa et al. (2015). [157]

2. HYPOTHESIS AND OBJECTIVES OF THE STUDY

2.1 Problem formulation

It is already known how uncorrected refractive errors can reduce the VA and the contrast sensitivity and that at low luminance levels the ocular aberrations are the main responsible for a decreased visual performance. However, there are no reports of how uncorrected refractive errors influence the perception of light distortion under low environmental lightning conditions. In this study it will be induced two different types of spherical defocus under cycloplegic conditions in order to investigate if there are differences on the perceived light distortion between a positive and negative defocus.

2.2 Hypothesis

The hypothesis of this thesis is that the defocus alters the light distortion perception and that the positive defocus increases the light distortion more than the negative defocus does due to the action of accommodation in normal healthy young eyes.

2.3 Objectives

The main goals of this thesis are:

1. Investigate the impact of positive and negative defocus on the perceived light distortion.
2. To understand how HOAs can affect the light distortion.
3. To analyze how topographic parameters such as SAI, SRI and Q can influence the light distortion.

3. MATERIAL AND METHODS

3.1 Study design

This was a cross-sectional study which intended to determine the impact of spherical defocus and high-order aberrations in light distortion measures around a LED (light emitting diode) light source.

The research was conducted in the Clinical and Experimental Optometry Research Lab (CEORLab) at the University of Minho (Braga, Portugal). All the instruments used in this study were available in the CEORLab. The protocol of the study was reviewed and approved by the Subcomité de Ética para as Ciências da Vida e da Saúde / Ethics Subcommittee for Health and Life Sciences (SECVS) of the University of Minho. Following the guidelines of the Declaration of Helsinki, all subjects signed a Consent Form (Attachment 1 on Appendix) once the objectives and procedures of the study were fully explained to them.

3.2 Participants and Sample Size

Sample size was calculated by GPower 3.1 software. To ensure an 80% power for a dependent comparison of means of light distortion between different levels of defocus, a sample size of 28 subjects was needed for a 0.05 level of significance.

In order to recruit participants for this study, it was sent an email to all academic community of the University of Minho. The inclusion criteria for this thesis project were subjects between 18 and 40 years of age, a spherical refractive error between +2.00 and -3.00D, with astigmatism below 1.50D and less than 1.00D of anysometropia. It was required transparent ocular media, no ocular pathology or surgery, and taking no ocular or systemic medications with ocular affectation. Subjects should present a best corrected VA of 0.00 LogMAR units or better in each eye, and the difference in VA between both eyes must be less than 0.1 LogMAR units.

Thirty-one (31) subjects answered the email and came to an initial consultation, however one (1) of them was unable to complete the experimental session. Thirty (30) subjects completed the study protocol. All subjects that volunteered to participate underwent a full optometric examination to assess suitability to enter the study and the required measurements were done at the Clinical and Experimental Optometry Research Lab (CEORLab) of the Center of Physics at University of Minho following the procedures described in the next section.

3.3 Experimental Procedure

3.3.1 Clinical Examination Routine

Once the subjects were recruited to participate in this study, an informed consent was signed in order to alert the subjects to the application of a cycloplegic solution (described in section 3.3.3). The experimental procedure started with the subjective refractive exam followed by the registration of high and low contrast distance LogMAR visual acuity and topographic measures. Then, aberrometry and light distortion measures were carried out with a natural mesopic pupil size measured in light distortion measurements luminance conditions. Light distortion measurements were first taken with the best distance correction only. Thirty minutes after the instillation of two drops of a cycloplegic solution, high and low contrast visual acuity, aberrometry and light distortion were re-evaluated. Aberrometry and light distortion were taken for a 5mm limited pupil diameter. In cycloplegic conditions light distortion was measured for the best distance correction and with the induction of a positive and negative defocus of 1.00D. All measures were made in one visit only.

3.3.2 Visual Acuity

High contrast (100%) (**Figure 3.1A**) and low contrast (10%) (**Figure 3.1B**) distance visual acuity (HCDVA and LCDVA, respectively) were measured with the Logarithmic Visual Acuity Chart EDTRS (Precision Vision. IL) at 4 meters (as recommended by the manufacturer). This visual acuity chart is constituted by 14 lines with 5 letters each and measure VA between 1.00 LogMAR units and -0.30 LogMAR units (that is equivalent to 0.10 and 2.00, respectively, in decimal scale). The line of 20/20 (or 1.0 in decimal scale) is equivalent to 0.00 (zero) in LogMAR scale. Each letter read means -0.02 LogMAR units and so VA is better if it is more negative or less positive. VA was evaluated under high (100%) (CAT No 2110) and low (10%) contrast (CAT No 2153) conditions using the Cabinet Illuminator No 2425.

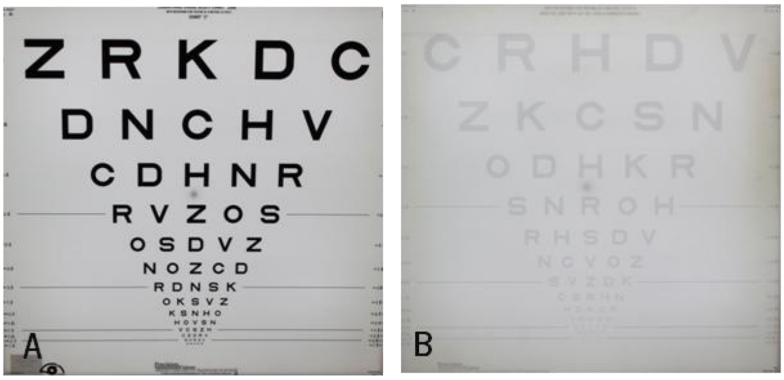


Figure 3.1 ETDRS chart for HCVA (A) and LCVA (B) measurement.

The VA was always monocularly and binocularly evaluated in the referred conditions with a room luminance at photopic levels (85cd/m^2) under non-cycloplegia and cycloplegia. The LCDVA was evaluated with the best distance visual correction, as the HCDVA, and with +1.00D and -1.00D lens.

3.3.3 Topography

Topographic measures were obtained with a corneal topographer (Medmont E300, Medmont Pty.Ltd, Melbourne, Australia) in order to evaluate how topographic quality parameters are related to light distortion. The topographic parameters registered were the corneal asphericity (Q-value), Surface Asymmetry Index (SAI) and Surface Regularity Index (SRI) once some authors [120 158-161] referred these as being predictors of the optical image quality. For the measurement, the subject was comfortably set in the chin up of the instrument and the mires focused (>95%) and it was instructed to blink and maintain the eye wide open. The measures were taken before the cycloplegic instillation and were recorded three measures, being considered their mean.

3.3.4 Cycloplegia

To know the mechanism behind the relationship between defocus and light distortion, it was necessary the use of a cycloplegic solution to avoid the effect of accommodation. The cycloplegia was obtained by the instillation of *Tropicil top* 10mg/ml eyedrop. The active substance of this eye solution is tropicamide, which is an anticholinergic drug that blocks the sphincter muscle and the ciliary body. This eyedrop has mydriatic and cycloplegic functions, being used on ophthalmic examinations and as therapeutical agent. To the required cycloplegia's effect it was instilled a dose of two drops of *Tropicil top* 10mg/ml on the conjunctival bag with a 5 minutes interval, and data collection was done 30 minutes after the second drop application, as recommended by the manufacturer.

3.3.5 Aberrometry

Aberrometry was measured using the IRx3 Hartmann-Shack aberrometer (ImaginEyes, France). Ocular high order aberrations (HOAs) were recorded under mesopic conditions before and after cycloplegic instillation. On each condition three measures were recorded for each eye. During HOAs measurement the subjects were asked to fixate on a red light spot on the "E" letter inside the aberrometer and to blink several times, maintaining the eye wide open after that in order to take a good quality measure. The aberrometer gave the total HOA values expressed as Zernike polynomials up to the sixth order (from Z_3^{-3} to Z_6^{6}). The aberrations considered for this study were Total HOA RMS (from from Z_3^{-3} to Z_6^{6}), Spherical-like HOA RMS (including Z_4^{0} and Z_6^{0}) and Coma-like HOA RMS (including Z_3^{-1}, Z_3^{1}, Z_5^{-1} and Z_5^{1}). All the aberrations were calculated for the natural pupil size from each subject under the measurement of light distortion in non-cycloplegic conditions and for a 5mm pupil diameter in cycloplegic conditions. The magnitude of each Zernike polynomial obtained by the aberrometer and then we calculated the Total, Spherical-like and Coma-like HOA RMS using Microsoft Excel spreadsheet (Microsoft Office 2010, Microsoft).

3.3.6 Light Distortion

Light distortion quantification was obtained from *Light Distortion Analyzer* (LDA, CEORLab, University of Minho, Braga, Portugal), a device validated by Ferreira-Neves et al. (2015) [136], under non-cycloplegic and cycloplegic conditions. This device measure the light distortion under more realistic and consistent conditions due to its physical LEDs.[136] LDA is constituted by a central LED surrounded by others 240 smaller LEDs distributed over 24 semimeridians with an angular separation of 15degrees. [119 135] According to Linhares et. al (2013) [135] the central LED has a maximum luminance of 2800 cd/m^2, with a radiance of 0.0751 W m^{-2} sr^{-1} at its maximum intensity, and 6 cd/m^2 for the surrounding LEDs, with a radiance of

0.000423 W m^{-2} sr^{-1} in the same conditions. The intensity drops 50% at a view angle of 50° in the central LED and at 120° in the surrounding LEDs. Their color is in the ΔE^*_{ab} range of 2.6 and 0.23, respectively.

For each examination, the software system derives different metrics:

- **The distortion area (DA)** is the sum of the areas of all sectors formed by each pair of semimeridians under analysis, in mm^2.
- **The Light distortion index (LDI)** is the percentage of the total tested area that is not visible because of impairment by the light distortion phenomena. It is given by the ratio of the area missed by the subject and the total area explored, expressed in percentage (%). Higher values of LDI are interpreted as the lower ability to discriminate surrounding small stimuli that are by the central source of light.
- **Best fit circle radius (BFCRad)** is a circle that best fits the DA whose radius, expressed in mm, is equal to the average length of the distortion along each semimeridian under evaluation.
- **Best fit circle center coordinates (XCoord and YCoord)** are defined as the Cartesian coordinates (x, y) in mm from the center of the display.
- **Orientation of best fit circle center (BFCOrient)** is the angle of BFC center from the origin of coordinates (0,0) (center of the display), expressed in degrees.
- **DA irregularity (BFCIrreg)** is the sum of the deviations between the actual DA and the BFC outer perimeter along all the semimeridians tested. It is a sum of positive and negative values as the limit of the distortion is in or out of the BFC perimeter and is expressed in mm.
- **SD of the BFC irregularity (BFCIrregSD)** is the sum of the differences squared and divided by the number of semimeridians tested (n), expressed in mm. Higher values of BFCIrregSD means a more irregular distortion.[136]

In this study it was used an in-out 30° routine exam. In this examination routine the peripheral LEDs are presented from the center to the periphery in 12 of the 24 semimeridians with a separation of 30° between them. First, and after a demonstration pre-test, it was evaluated the light distortion under non-cycloplegic conditions with the best distance visual correction. Under cycloplegia, subjects' light distortion was randomly measured monocularly and binocularly with the best distance visual correction and with a positive and negative defocus of 1.00D. A diaphragm of 5mm was used to standardize the pupil size of all subjects under cycloplegia, even in binocular conditions. In this study were used two metrics to quantify the size of the distortion (the LDI and the BFCRad) and two metrics to evaluate the irregularity of the distortion (BFCIrreg, BFCIrregSD).

All light distortion measures were taken under low room illumination (0.913±0.017LUX) measured with a Minolta T-10 luminanciometer.

3.3.7 PSF Simulation

In order to compare the psychophysical measures of light distortion size obtained with LDA with an optical metric, we simulated for each subject the monocular PSF. For the PSF simulations we used the MATLAB (The MathWorks, Inc., USA), having in account the wavefront aberrometry of the randomized eyes, the best distance refraction, the pupil size and the positive and negative induced defocus of 1.00D. We compared the BFCRad values (LDA size parameter) with the size of the PSF in arcmin reproduced by MATLAB for both positive and negative induced defocus in cycloplegic conditions. Besides we also simulated the PSFs for different levels of positive and negative defocus (since -1.50D to +1.50D in 0.50D steps) with the best distance correction for three situations: 1) without cycloplegia and the mean natural pupil size in mesopic conditions; 2) with cycloplegia and a 5mm pupil not allowing any degree of accommodation; 3) with cycloplegia and a 5mm pupil allowing a maximum accommodation of 0.50D (assuming that tropicamide did not totally stopped the accommodation).

3.4 Statistical Analysis

Statistical analysis was performed with SPSS Statistic software version 23.0 (SPSS Inc, Chicago, IL). The descriptive data are presented in terms of mean±standard deviation. The normality of all variables was evaluated using the Kolmogorov-Smirnov test, since the sample was equal to 30. In the normality test, if the parameter of statistical significance (p) was less than 0.050, the null hypothesis was rejected, meaning that there were significant statistical differences in the distribution of the sample compared to a sample with normal distribution. If the alternative hypothesis was accepted, is because there are no differences to the normal distribution and the variable in question has a normal distribution. When 2 variables were compared, for example the comparisons between light distortion parameters with a positive and a negative defocus, the Paired Samples T-Test was used for variables with normal distribution and Wilcoxon for those who do not fulfill this assumption of normality. The majority of the variables had a non-parametric distribution, so almost all the comparisons were made by using the paired Wilcoxon test. Whenever are presented differences, the values refers to the difference between the first condition (non-cycloplegic or without defocus or with positive defocus) minus the second condition (cycloplegic or with any type of defocus or negative defocus).

The correlations were performed by Pearson test if the variables had a normal distribution; otherwise the Spearman correlation was used. The correlations were considered strong if >0.800, moderately strong if between 0.500 and 0.800, fair if between 0.300 and 0.500 and poor if <0.300. [162]

The level of significance of the study was set at α=0.050.

4. RESULTS

In order to know if both eyes (right and left) would be considered for the statistical analysis for the purpose of this study, it was firstly made a statistical analysis to know the differences between the two eyes. From the results obtained by comparing the right and left eye (**Table 9.1** from Attachment 2 on appendix) in non-cycloplegic and cycloplegic conditions is observed that the differences between the two eyes are very low and have no statistical significance (p >0.050 for all parameters). **Figure 4.1** represents the differences between both eyes for the refractive components and shows that the differences are very small, being almost identical for M and J0.

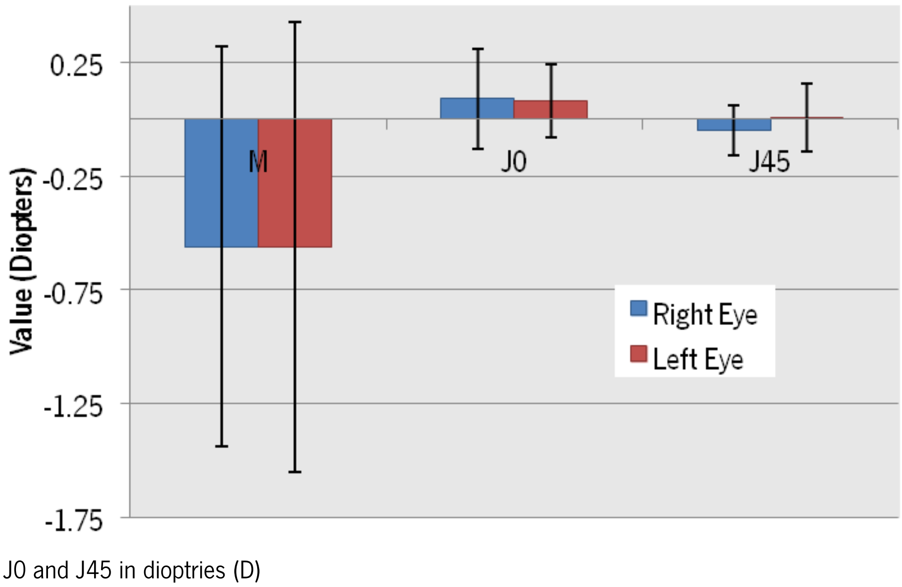


Figure 4.1 Magnitude of the refractive components (M, J0 and J45) from the right and left eyes.

Besides, both eyes were in general strongly and significantly correlated. This analysis led us to randomize the choice of only one eye per subject to deal with the monocular findings and so, from here, we only refer to monocular values considering the randomization process.

4.1 Sample Characteristics

The characteristics of the sample are presented in **Table 4.1** for non-cycloplegic conditions.

Table 4.1 Demographic characteristics of the sample expressed in Mean±SD.

Parameter	Description
n	30
AGE (years)	23.28±3.61
GENDER	21 female (70%) 9 male (30%)
M (D)	-0.56±0.92
J0 (D)	0.07±0.17
J45 (D)	-0.02±0.13
Pupil Size at mesopic conditions (mm)	5.64±0.65
Q_{mean}	0.28±0.11
SIM K_{mean} (mm)	43.90±1.44
IS index (D)	-0.21±0.47
SRI	0.48±0.15
SAI	0.60±0.17

M: Equivalent Sphere; J0: differences on dioptric power between the horizontal and vertical meridians; J45: oblique astigmatism; All the parameters are expressed as mean±SD, except the sample size (n) and the gender.

4.2 Visual Acuity

The visual acuity was measured under non-cycloplegic and cycloplegic conditions and for different high and low contrast with the best distance correction. Low contrast distance visual acuity with the best distance correction was also measured with an additional positive and negative induced defocus of 1.00D. The LogMAR values for each condition and the significance between the non-cycloplegic and cycloplegic conditions are presented in **Table 4.2**.

Table 4.2 Monocular and binocular LogMAR visual acuity (Mean±SD) measured in non-cycloplegic and cycloplegic conditions for four different conditions.

	HCDVA	LCDVA	LCDVA+1D	LCDVA-1D
MONOCULAR CONDITIONS				
WITHOUT CYCLOPLEGIA	-0.15±0.08	0.02±0.06	0.42±0.13	0.05±0.10
WITH CYCLOPLEGIA	-0.09±0.07	0.13±0.09	0.41±0.24	0.29±0.19
p	**<0.001+**	**<0.001***	0.927+	**<0.001+**
BINOCULAR CONDITIONS				
WITHOUT CYCLOPLEGIA	-0.19±0.07	-0.03±0.06	0.30±0.11	-0.01±0.08
WITH CYCLOPLEGIA	-0.14±0.07	0.08±0.07	0.41±0.13	0.28±0.12
p	**0.003***	**<0.001+**	**<0.001+**	**<0.001+**

HCDVA: high contrast visual acuity with the best distance correction; LCDVA: low contrast visual acuity with the best distance correction; LCDVA+1D: low contrast visual acuity with the best distance correction and a positive induced defocus of +1.00D; LCDVA-1D: low contrast visual acuity with the best distance correction and a negative induced defocus of -1.00D; Statistically significant differences are presented in **bold**; (*) Wilcoxon Signed Ranks Test; (+) Paired Samples T-test.

All subjects had a monocular and binocular high contrast VA (HCDVA) $\leq$ 0.00 LogMAR with the best distance visual correction for non-cycloplegic and cycloplegic conditions. The binocular VA was always higher than the monocular VA under all conditions. Comparing the VA without cycloplegia with the VA with cycloplegia it is observed that the differences are statistical significant (p<0.010) under all conditions, except for the monocular condition of the low contrast visual acuity with a positive +1.00D of induced defocus (LCDVA+1D) (p>0.050, Paired samples T-test). In general, all the VA measurements are lower (more positive LogMAR values) after the cycloplegic instillation.

Table 4.3 Monocular and binocular differences (Mean±SD) between the four conditions tested (LogMAR scale) measured without and with cycloplegia.

		HCDVA	LCDVA+1D	LCDVA-1D
MONOCULAR CONDITIONS				
WITHOUT CYCLOPLEGIA	**LCDVA**	-0.17±0.06 **<0.001***	-0.40±0.13 **<0.001***	-0.03±0.07 0.062*
	LCDVA+1D	-	-	0.37±0.15 **<0.001**
WITH CYCLOPLEGIA	**LCDVA**	-0.26±0.12 **<0.001***	-0.35±0.19 **<0.001***	-0.20±0.16 **<0.001***
	LCDVA+1D	-	-	-0.14±0.21 **0.004**+
BINOCULAR CONDITIONS				
WITHOUT CYCLOPLEGIA	**LCDVA**	-0.16±0.06 **<0.001***	-0.33±0.10 **<0.001**+	-0.01±0.06 0.266+
	LCDVA+1D	-	-	0.32±0.13 <0.001+
WITH CYCLOPLEGIA	**LCDVA**	0.12±0.08 **<0.001**+	0.38±0.16 **<0.001**+	0.30±0.13 **<0.001**+
	LCDVA+1D	-	-	-0.08±0.18 **0.001**+

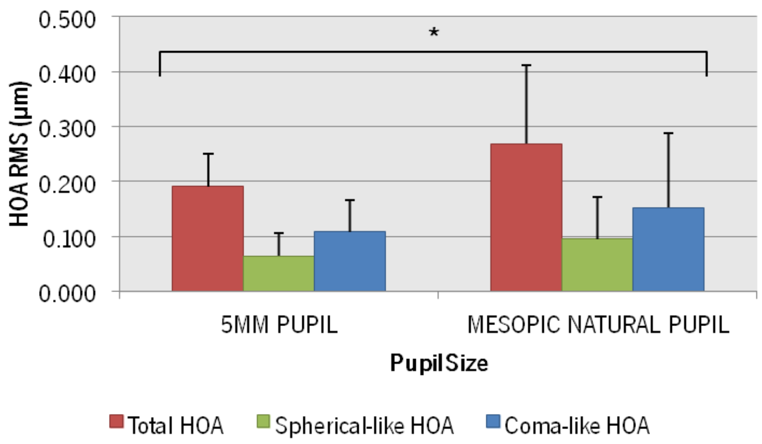
HCDVA: high contrast visual acuity with the best distance correction; LCDVA: low contrast visual acuity with the best distance correction; LCDVA+1D: low contrast visual acuity with the best distance correction and a positive induced defocus of +1.00D; LCDVA-1D: low contrast visual acuity with the best distance correction and a negative induced defocus of -1.00D; Statistically significant differences are presented in **bold**; (*) Wilcoxon Signed Ranks Test; (+) Paired Samples T-test.

In **Table 4.3** are presented the differences between the conditions of monocular and binocular VA measured for both cycloplegic conditions. It can be observed that the LCDVA was significantly ($p<0.010$) lower (more positive LogMAR values) than the HCDVA under all conditions by more than one VA line. LCDVA+1D and LCDVA-1D were always worse than the LCDVA. With the positive induced defocus the mean LCDVA was lower than with the negative induced defocus. The differences were statistically significant ($p<0.010$) for all the measurements, except for the monocular and binocular VA values between the LCDVA and LCDVA-1D without cycloplegia.

4.3 High Order Aberrations

Table 4.4 Total HOA, Spherical and Coma RMS aberrations (Mean±SD) under non-cycloplegic and cycloplegic conditions with the respective pupil size during the measurements.

	TOTAL HOA RMS (μm)	SPHERICAL HOA RMS (μm)	COMA HOA RMS (μm)
MONOCULAR CONDITIONS WITHOUT CYCLOPLEGIA			
NATURAL MESOPIC PUPIL (5.64±0.65MM)	0.269±0.144	0.095±0.077	0.152±0.135
5MM PUPIL	0.190±0.061	0.066±0.045	0.099±0.061
MONOCULAR CONDITIONS WITH CYCLOPLEGIA			
5MM PUPIL	0.191±0.060	0.065±0.041	0.109±0.058



(*) Differences were statistically significant with Wilcoxon Signed Ranks Test

Figure 4.2 Distribution of high order aberrations (spherical-like, coma-like and total RSM up to 6th order) for the two pupil sizes considered when measured and analyzed the light distortion. Mesopic natural pupil refers to the average pupil size of the sample (5.64±0.65mm).

The distribution of the HOA is variable between the participants. In this sample the comatic HOA was always higher than the spherical HOA at both non-cycloplegic and cycloplegic conditions (**Table 4.4**). The differences between the non-cycloplegic and cycloplegic values for the HOA were only statistically significant when compared with different pupil size (**Table 4.5**). For a 5mm pupil the differences between HOA in non-cycloplegic and cycloplegic conditions were not statistically significant. In **Figure 4.2** it can be observed that all the HOA increased with the increase of pupil size, once the mesopic natural pupil size is approximately 0.64mm larger than the 5mm pupil size limited by a diaphragm for cycloplegic measurements.

Table 4.5 Differences in Total HOA, Spherical-like and Coma-like RMS aberrations (Mean±SD) between non-cycloplegic and cycloplegic measures for the respective pupil sizes.

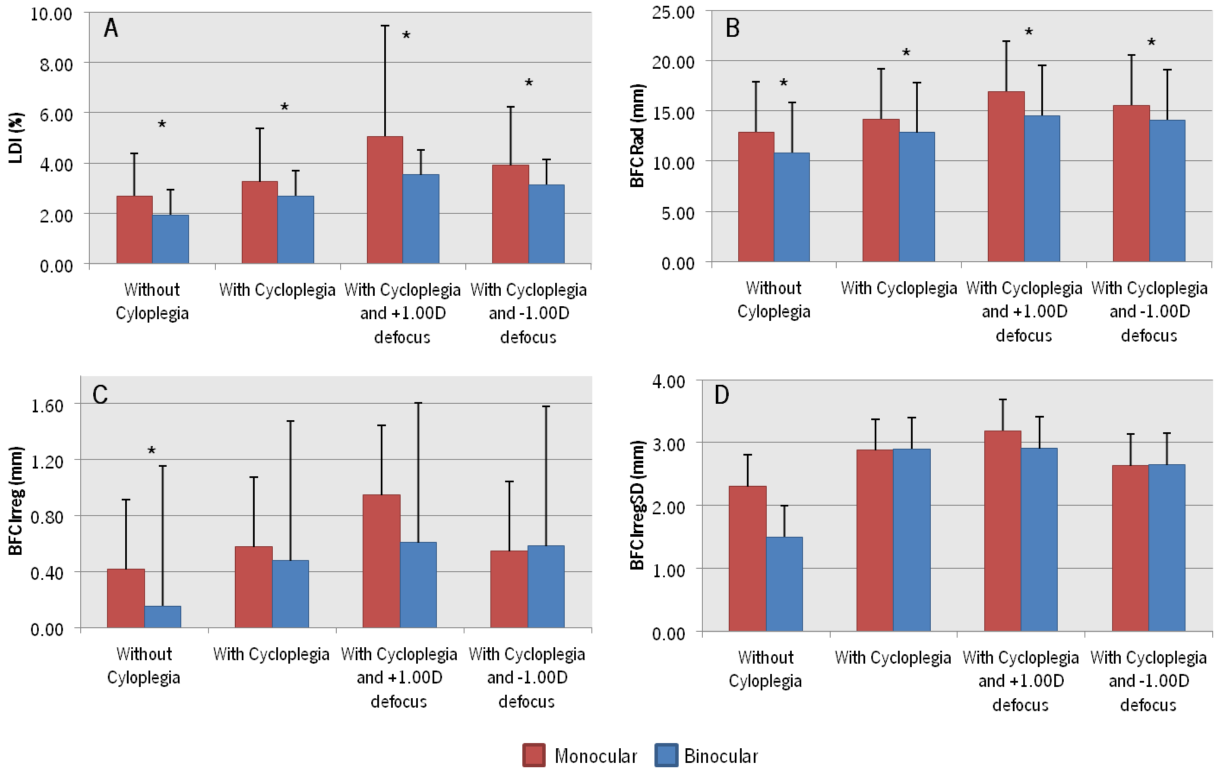
		TOTAL HOA	SPHERICAL HOA	COMA HOA
			Difference±SD *p*	
			5MM PUPIL WITH CYCLOPLEGIA	
WITHOUT CYCLOPLEGIA	NATURAL MESOPIC PUPIL	0.078±0.123 **0.001***	0.031±0.049 **0.003***	0.044±0.105 **0.037***
	5MM PUPIL	-0.001±0.051 0.898+	0.001±0.018 0.616*	-0.010±0.044 0.141*

Statistically significant differences are presented in **bold**; (*) Wilcoxon Signed Ranks Test; (+) Paired Samples T-test.

4.4 Light Distortion Analysis

4.4.1 Comparison between monocular and binocular measures

The light distortion parameters were recorded from LDA for monocular and binocular conditions under cycloplegic and non-cycloplegic conditions. **Figure 4.3** represents the graphical results from the differences between monocular and binocular light distortion parameters measured. Barplots A and B refer to light distortion size parameters and barplots C and D to light distortion irregularity parameters.



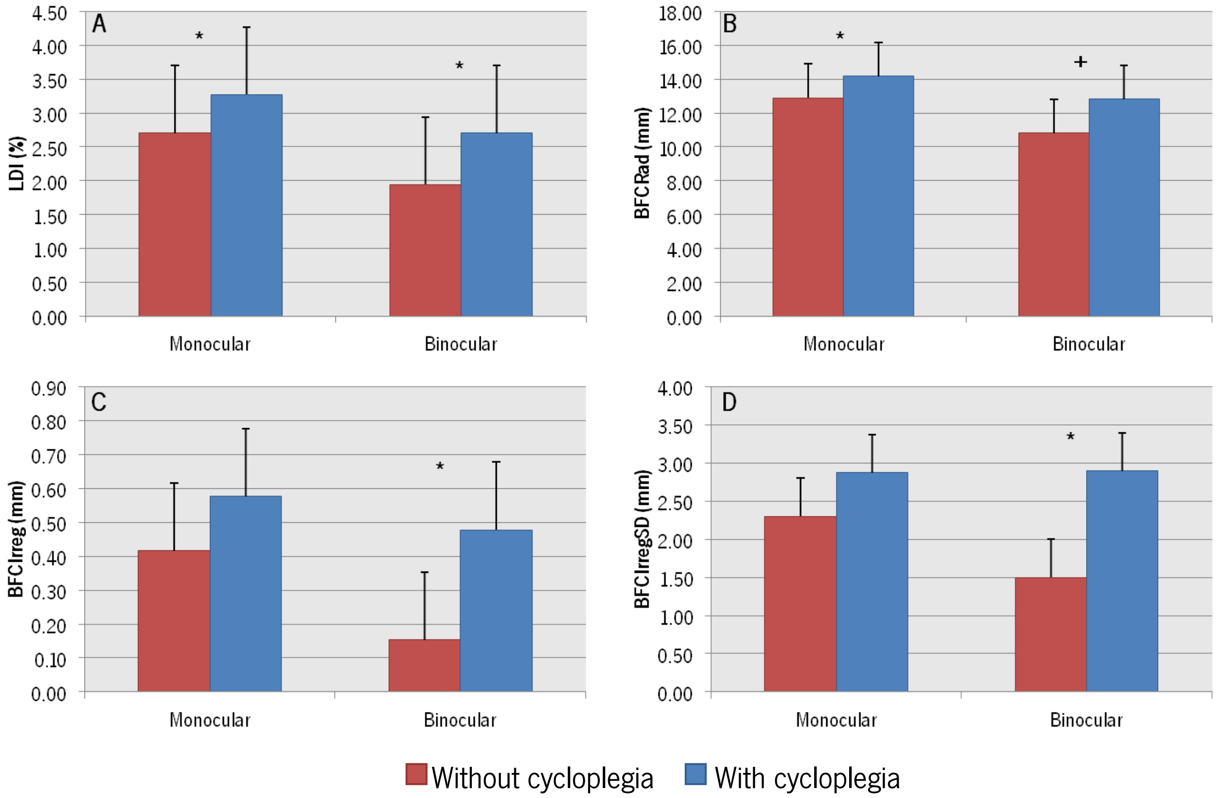
(*) Differences were statistically significant with Wilcoxon Signed Ranks Test.

Figure 4.3 Mean±SD light distortion size (barplots A and B) and irregularity (barplots C and D) monocular and binocular measures. Statistical differences were found between the monocular and binocular measures for all conditions on light distortion size parameters (LDI and BFCRad).

From **Figure 4.3** it s observed that monocular values were always higher than the binocular values for all parameters, in all the conditions measured. This was always true except for BFCIrreg under cycloplegic conditions with an induced defocus of -1.00D and for BFCIrregSD at cycloplegia only with the best distance correction. It was found differences statistically significant for LDI and BFCRad (barplots A and B) (all $p<0.050$, Wilcoxon) between monocular and binocular measures in the four conditions presented (without cycloplegia, with cycloplegia, with cycloplegia and a positive and negative induced defocus of 1.00D). For the irregularity light distortion parameters (barplots C and D) no statistically significant differences ($p>0.050$, Wilcoxon) between monocular and binocular measures were found, except for the BFCIrreg in non-cycloplegic condition ($p<0.010$, Wilcoxon). In addition, the correlations between monocular and binocular measures were significantly positive and moderatly strong or strong for size parameters (r>0.500, p<0.010, Spearman correlation) and non-significantly low for irregularity parameters (see **Table 9.2** from Attachment 2 on appendix).

4.4.2 Comparison between non-cycloplegic and cycloplegic measures

In order to study if the cycloplegic has influence on light distortion perception, we compared the LDA parameters in both cycloplegic conditions (without and with cycloplegia) with the best distance correction. In **Figure 4.4** are represented the results from the mean and standard deviation of the monocular and binocular light distortion values in non-cycloplegic and cycloplegic conditions in plotbars.



(*) Differences were statistically significant with the Wilcoxon Signed Ranks Test); (+) Differences were statistically significant with the Paired samples T-test.

Figure 4.4 Comparison between monocular and binocular light distortion size (barplots A and B) and irregularity (barplots C and D) between non-cycloplegic and cycloplegic measures.

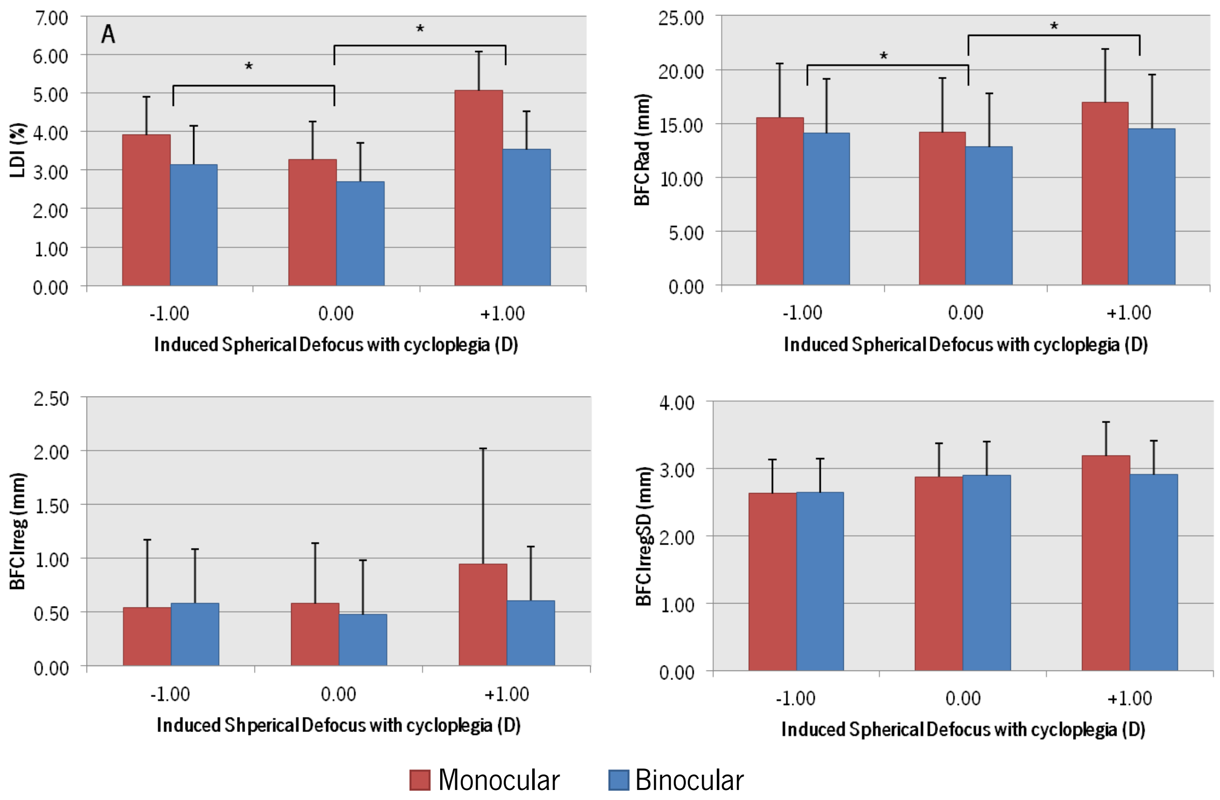
From **Figure 4.4** it can be observed that both monocular and binocular LDA values with cycloplegia tend to be more elevated than without cycloplegia. All the differences were statistically significant (p<0.050, Wilcoxon and T-test), except for the monocular measures of BFCIrreg and BFCIrregSD (p>0.050, Wilcoxon). It was also observed that once again there are positive moderatly strong and significant correlations between the LDI without and with cycloplegia in both monocular (r=0.793, p<0.001, Spearman) and binocular (r=0.618, p<0.001, Spearman) conditions. The same it was observed for the BFCRad correlation between non-cycloplegic and cycloplegic values for monocular (r=0.753, p<0.001, Pearson) and binocular (r=0.635, p<0.001, Pearson) conditions (see **Table 9.3** from Attachment 2 on appendix).

From the same figure we can also observe if there is a relatioship between the pupil size and light distortion measures, once the pupil size were different in non-cycloplegic (5.64±0.65mm) and cycloplegic (5mm limited pupil) conditions.

According with these results, under cycloplegia the amount of light distortion perceived is always major than without cycloplegia, incresing its size and irregularity.

4.4.3 Impact of defocus on Light Distortion measures

Figure 4.5 shows the monocular and binocular results of light distortion for each parameter evaluated by LDA in cycloplegic conditions with a limited pupil size of 5mm, and the three comparisons (1. No induced defocus vs. +1.00D induced defocus; 2. No induced defocus vs. -1.00D induced defocus; 3. +1.00D induced defocus vs. -1.00D induced defocus). **Table 9.4** from Attachment 2 (on appendix) represents the Mean±SD differences values, correlations and significances for each parameter in monocular and binocular conditions for each compared pairs.



(*) Differences were statistically significant with Wilcoxon Signed Ranks Test.

Figure 4.5 Comparison between monocular and binocular LDA size (A and B) and irregularity (C and D) values (Mean±SD) represented in barplots for negative, zero and positive (-1.00D, 0.00D and +1.00D, respectively) induced spherical defocus in cycloplegic conditions for a 5mm pupil.

As in section 4.4.1 we can observe that the binocular values of light distortion were always lower than the monocular one, being the differences statistically significant for LDI and BFCRad ($p<0.01$, Wilcoxon) (see **Table 9.2** from Attachment 2 on appendix). However, here we can better observe that the BFCIrregSD suffered minor changes between monocular and binocular measures.

Both negative and positive induced defocus increased size parameters of light distortion (graph A and B from **Figure 4.5**) compared to the values observed with no induced blur (0.00D of induced defocus). However, the same did not happen for irregularity parameters. BFCIrreg obtained in the situation with negative induced defocus did not change comparing to the situation with no induced blur and BFCIrregSD had slightly decreased.

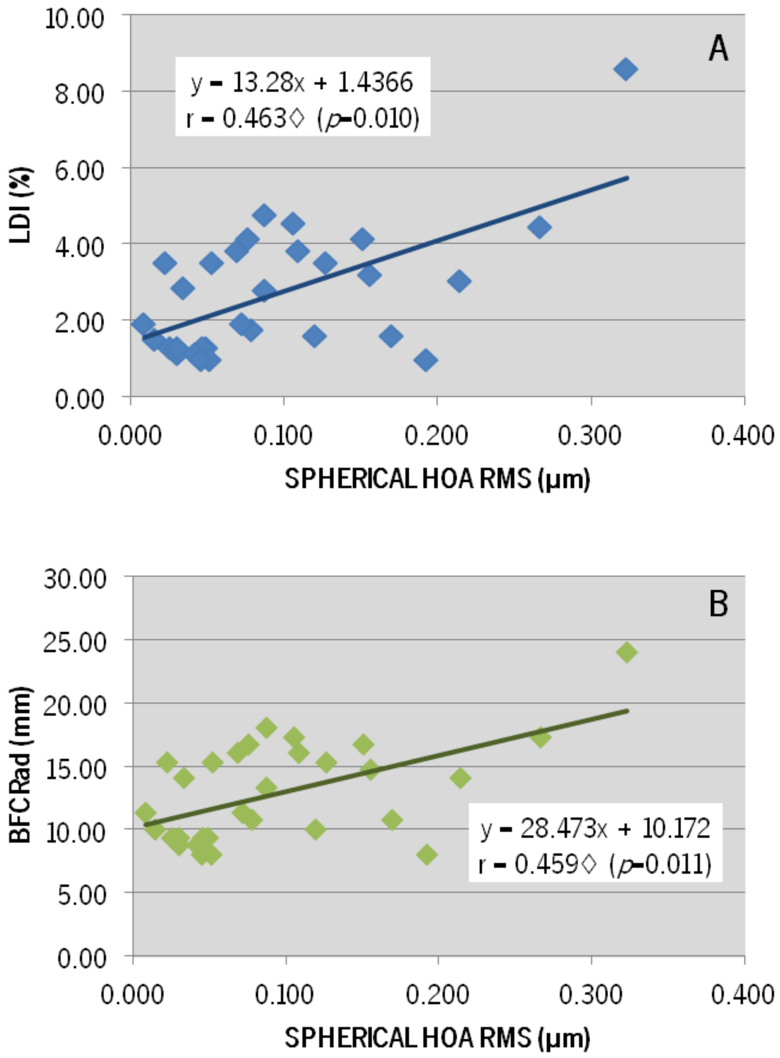
Comparing the results obtained for each level of induced blur, it can be observed that the higher light distortion was achieved by the induction of a positive defocus of +1.00D for all the parameters evaluated (LDI, BFCRad, BFCIrreg and BFCIrregSD). When simulated a +1.00D defocus the perceived light distortion was larger than with no level of induced defocus and with

-1.00D defocus. The differences were statistically significant (*p*<0.050, Wilcoxon) for the monocular and binocular LDI and BFCRad between the situation with no induced defocus with the positive and negative induced defocus situations, except for the comparison of the binocular LDI between no level of defocus and negative induced defocus (*p*=0.056, Wilcoxon). For the BFCIrreg and BFCIrregSD parameters the differences were never statistically significant (*p*>0.050, Wilcoxon). When compared the positive induced defocus with the negative induced defocus the differences were not statistically significant (*p*>0.050, Wilcoxon) for any light distortion parameters.

The LDI without induced defocus situation was significantly and moderately to strongly correlated with the LDI with positive (r=0.752, *p*<0.001, Spearman correlation) and negative (r=0.560, *p*=0.001, Spearman correlation) induced defocus situations under monocular conditions. Under binocular conditions the correlation was also significant and moderately strong (see **Table 9.4** from Attachment 2 on appendix). The same was observed for the BFCRad. On the comparison of the light distortion parameters between the positive and negative induced defocus situation, the LDI and the BFCRad had a significant moderately strong correlation (r>0.500, *p*<0.010, Spearman correlation) for monocular and binocular conditions (see **Table 9.4** from Attachment 2 on appendix). For the BFCIrreg and BFCIrregSD parameters the correlations were not statistically significant (*p*>0.050, Spearman correlation).

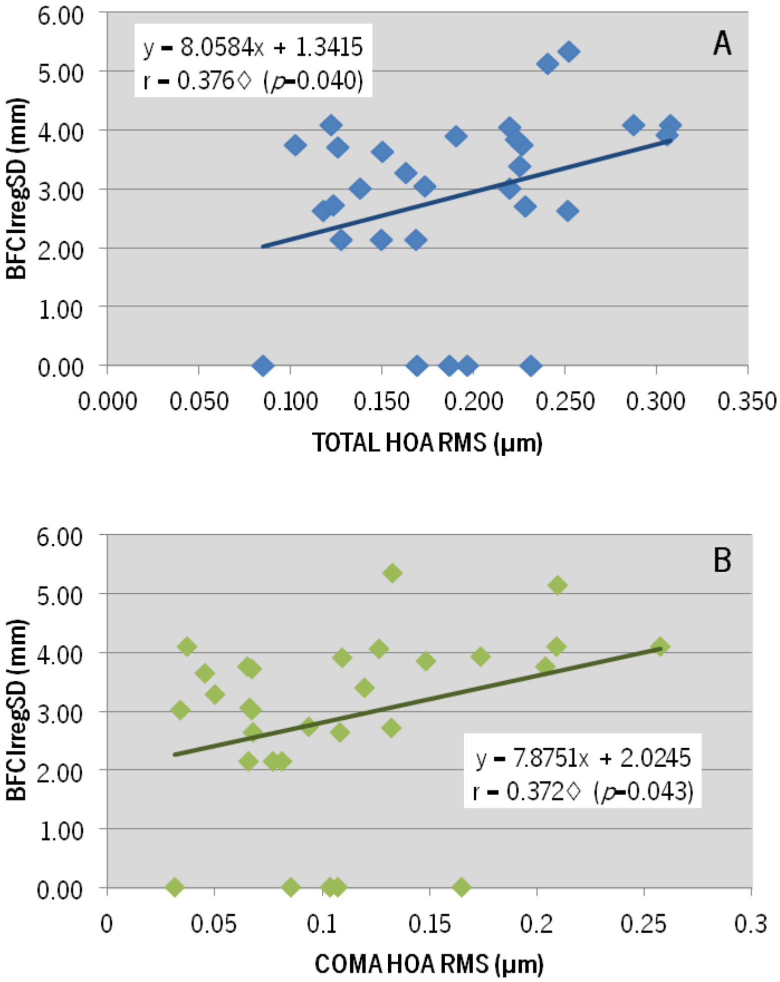
4.5 Impact of High Order Aberration on Light Distortion

On **figures 4.6** and **4.7** are represented the graphical correlations of the high order aberrations with LDA parameters. **Figure 4.6** represents the relationship of LDI (graph A) and BFCRad (graph B) with the spherical-like high order aberration (spherical-like HOA RMS) without cycloplegia (5.64±0.65mm pupil) and **Figure 4.7** represents the relationship of BFCIrregSD with the total HOA (graph A) and the coma HOA RMS (graph B) with cycloplegia (5mm pupil). Only the statistically significant (*p*<0.050, Spearman correlation) correlations are graphically presented (see **Table 9.5** from Attachment 2 on appendix for remaining correlations).



(◊) Spearman correlation

Figure 4.6 Correlations of spherical-like high order aberration with light distortion index (LDI) and best fit circle radius (BFCRad) (graph A and B, respectively) without cycloplegia.



(◊) Spearman correlation

Figure 4.7 Correlations of total and coma high order aberrations with best fit circle irregularity standard deviation (graph A and B, respectively) with cycloplegia.

Under non-cycloplegic conditions the size parameters (LDI and BFCRad) were significantly and fairly ($r>0.300$, $p<0.050$, Spearman correlation) correlated with the spherical aberration. In these non-cycloplegic conditions, any other high order aberration was correlated with any other light distortion parameter. In graphs from **Figure 4.6** we noticed the existence of an outlier. After removal the subject with the highest value of spherical-like HOA the correlation coefficient reduced slightly in some cases but the correlations remained fair and statistically significant so that the conclusions of the work do not change because of this subject with a somewhat atypical behaviour and that seemed, at first glance, to alter the linear correlation coefficient. The same applies to other parts of the results.

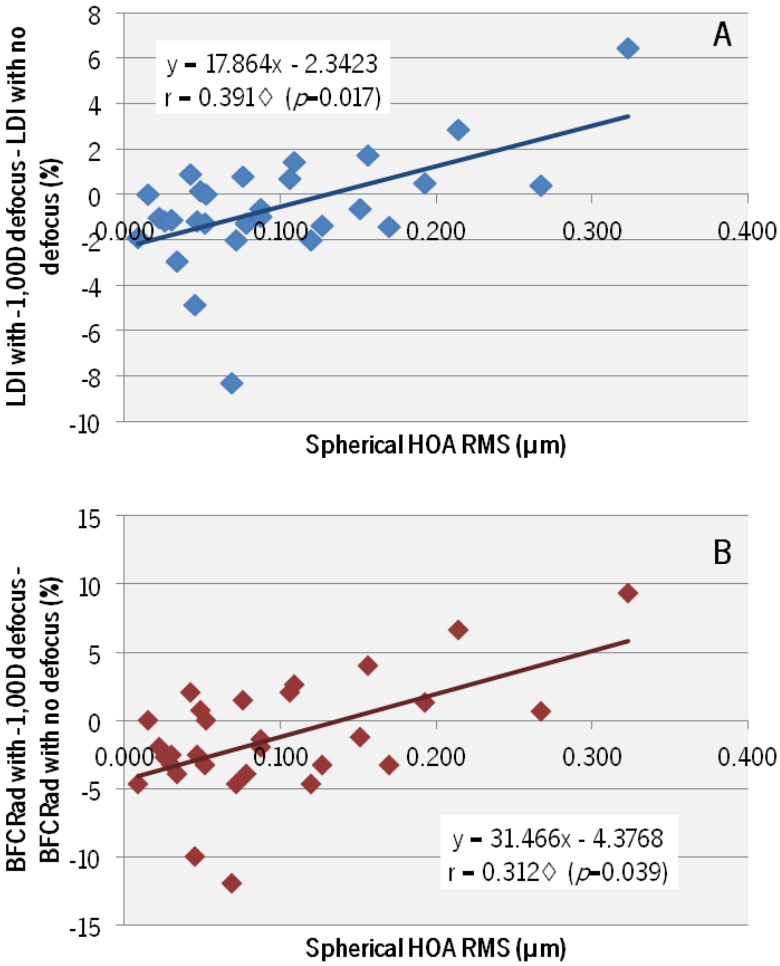
On the other hand, with cycloplegia and with no induced defocus the BFCIrregSD, an irregularity parameters of light distortion, showed a fairly significant correlation (r>0.300, p<0.050, Spearman correlation) with total and coma high order aberrations, being their values very similar. There were no other statistically significant correlations between other parameters (see **Table 9.5** from Attachment 2 on appendix for further detail).

Table 4.6 Correlations between the high order aberrations (for a 5mm pupil) and the changes on light distortion parameters with cycloplegia. The changes in light distortion parameters are between no induced defocus and positive induced defocus, and no induced defocus and negative induced defocus. Statistically significant correlations are highlighted in bold.

	LDI	**BFCIRREG**	**BFCIRREGSD**	**BFCRAD**
WITH THE CHANGES ON LIGHT DISTORTION WITH +1,00D				
TOTAL HOA	-0.137 0.688◊	-0.243 0.453◊	0.190 0.330◊	-0.139 0.685◊
SPHERICAL HOA	-0.181 0.937◊	-0.147 0.204†	0.007 0.972◊	-0.230 0.806◊
COMA HOA	-0.078 0.938◊	-0.187 0.475◊	0.244 0.294◊	-0.051 0.747◊
WITH THE CHANGES ON LIGHT DISTORTION WITH -1,00D				
TOTAL HOA	0.113 0.656◊	-0.003 0.988†	0.160 0.450◊	0.076 0.690†
SPHERICAL HOA	<u>0.391</u> **0.017**◊	0.326 0.060◊	0.035 0.490◊	<u>0.312</u> **0.039**◊
COMA HOA	0.189 0.667◊	-0.263 0.201◊	0.140 0.460†	0.088 0.645†

Statistically significant correlations are presented in **bold** and the <u>underlined</u> values refers to a fairly correlation (r>0,300); (◊) Spearman correlation; (†) Pearson correlation.

Table 4.6 shows the correlations between high order aberrations and the changes on light distortion parameters with the two types of defocus (positive and negative) under cycloplegic conditions. In general, the correlations are very poor and with no statistical significance. However, spherical aberration showed a fairly positive and significant correlation with LDI (r=0.391, p=0.017, Spearman correlation) and BFCRad (r=0.312, p=0.039, Spearman correlation) when the change on light distortion with the negative defocus is considered. **Figure 4.8** represents both LDA size parameter changes correlations with the spherical aberration.



(◊) Spearman correlation

Figure 4.8 Correlation graphs between spherical high order aberration magnitude and the change on LDI (A) and BFCRad (B) when induced a negative defocus under cycloplegia. Aberrations report to the naked eye and not the combination of the inherent aberrations of the eye and defocus induced.

The correlation between the changes on high order aberrations magnitude and the changes on light distortion values without and with cycloplegia were also studied (**Table 4.7**). The change of each HOA and light distortion parameters can be observed on **Table 4.5** and **Table 9.3** from Attachment 2 on appendix (in monocular conditions), respectively. The results suggested that there were no statistically significant correlations between the change of HOA and the change on light distortion between non-cycloplegic and cycloplegic situations.

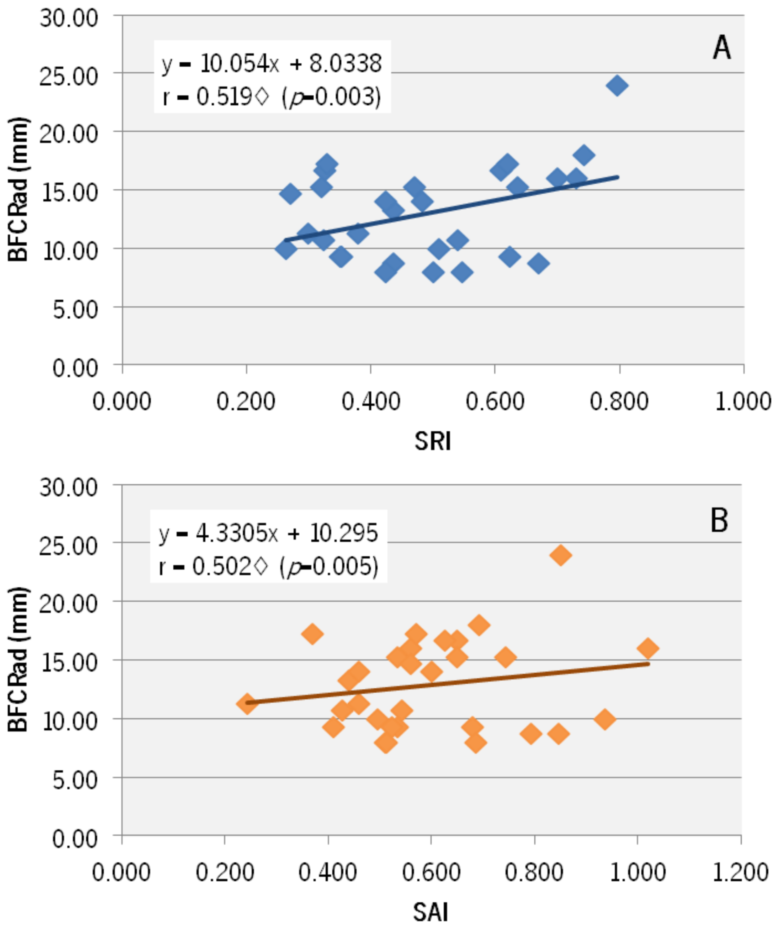
Table 4.7 Correlations between the changes on high order aberrations and the changes on light distortion parameters. The changes are between non-cycloplegic values and cycloplegic values. No statistically significant correlations were found.

	LDI	BFCRad	BFCIrreg	BFCIrregSD
TOTAL HOA	-0.051 0.911◊	0.004 0.981†	0.048 0.800†	-0.269 0.140◊
SPHERICAL HOA	-0.124 0.514†	0.014 0.941†	-0.034 0.759◊	-0.089 0.641†
COMA HOA	-0.055 0.883◊	-0.023 0.906†	0.167 0.377†	-0.265 0.158†

(◊) Spearman correlation; (†) Pearson correlation.

4.6 Light Distortion and Topographic quality parameters

According to the results obtained and presented on **Table 9.6** from Attachment 2 (on appendix) the corneal asphericity (Q) was not correlated with light distortion parameters under natural conditions (without cycloplegia). On the other hand, were found some significant correlations for SRI and SAI with BFCRad, a size light distortion parameters under non-cycloplegic conditions, that are graphically presented in **Figure 4.9**.



(◊) Spearman correlation

Figure 4.9 Correlation graphs of the BFCRad with SRI (A) and with SAI (B). The equation of the linear adjusted line is presented, as well the coefficient of correlation and its significance.

SRI had a moderately strong positive and significant correlation with BFCRad without cycloplegia (**Figure 4.9A**). SAI presented a moderately strong significant positive correlation with the BFCRad (**Figure 4.9B**) and fairly significant correlation with the BFCIrreg (r=0.371, *p*=0.044, Spearman correlation) (see **Table 9.6** from Attachment 2 on appendix).

4.7 Relationship between Light Distortion and Visual Acuity

Table 4.8 represent the monocular changes on LCDVA associated to the changes on light distortion parameters with the induced defocus used in this study under cycloplegia. A mean decrease on LCDVA of 0.35±0.19 LogMAR with the induced defocus of +1.00D is associated to an increase on light distortion size (at about of 1.80±3.68% in LDI and 2.75±5.06mm in BFCRad) and irregularity (0.37±1.16mm and 0.31±2.45mm on BFCIrreg and BFCIrregSD, respectively). With a induced defocus of -1.00D the LCDVA decreased on average by 0.20±0.16 LogMAR, being associated to an increase in LDI and BFCRad too, but in a lower level than with the positive defocus (0.64±2.44% and 1.38±4.26mm, respectively), and to a decrease on BFCIrreg and BFCIrregSD (-0.03±0.78mm and -0.24±2.40mm, respectively). All the referred changes are presented in **Table 4.3** and **Table 9.4** from Attachment 2 (on appendix) and they were statistically different for all the parameters.

Table 4.8 Monocular differences on LCDVA and light distortion parameters in their own units with the positive and negative defocus, in cycloplegic conditions.

CHANGE ON LCDVA (LogMAR)	CHANGES ON LIGHT DISTORTION PARAMETERS			
	LDI (%)	**BFCRad (mm)**	**BFCIrreg (mm)**	**BFCIrregSD (mm)**
WITH POSITIVE INDUCED DEFOCUS				
-0,35±0,19	-1,80±3,68	-2,75±5,06	-0,37±1,16	-0,31±2,45
WITH NEGATIVE INDUCED DEFOCUS				
-0,20±0,16	-0,64±2,44	-1,38±4,26	0,03±0,78	0,24±2,40

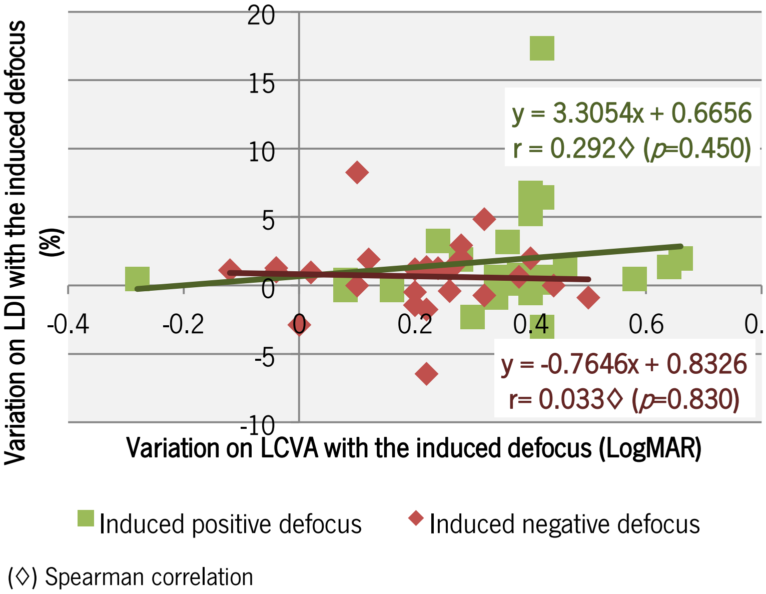
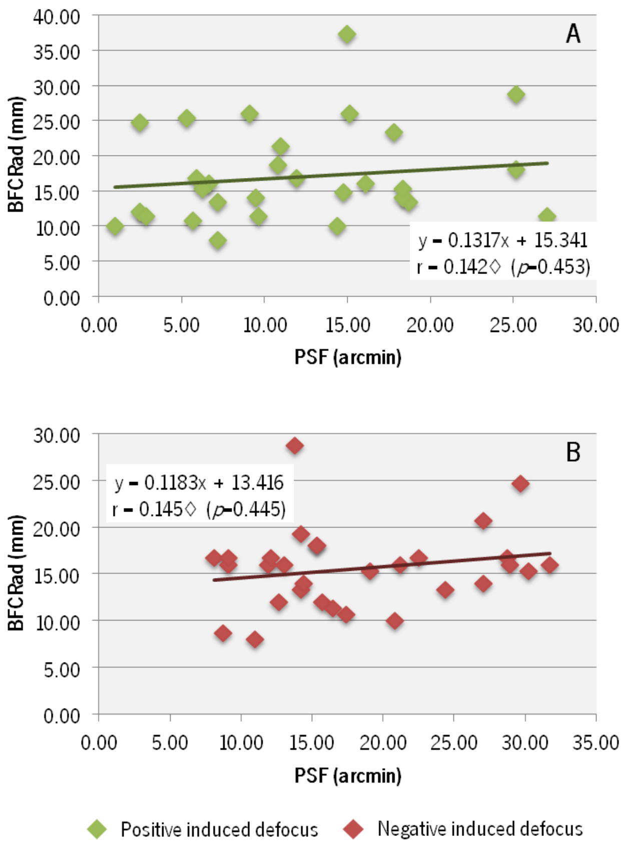


Figure 4.10 Correlation of the changes on LCDVA with the changes on LDI with the positive (green) and negative (red) induced defocus. The results show poor and non-significant correlations.

No significant correlations were found between the changes on LCDVA with the positive and negative defocus in cycloplegic conditions and the changes on light distortion parameters with cycloplegia with positive and negative induced defocus. Besides all the correlations were poor (all r<0.300, *p*>0.050, Spearman and Pearson correlations) (see **Table 9.7** from Attachment 2 on appendix). **Figure 4.10** represents the correlations above described where it can be seen the poor adjustment of the points to the linear correlation line in both positive and negative induced defocus situations for LDI parameter.

4.8 Light distortion size and PSF

Figure 4.11 represents the relationship between the BFCRad (mm), a size parameter of light distortion given by LDA, and the simulated PSF (arcmin) generated with a MATLAB program. Both graphs show a poor and non-significant correlation (r<0.300, *p*>0.050, Spearman correlation) between the two variables.



(◊) Spearman correlation

Figure 4.11 Correlation between the radius of the best fit circle adjusted (BFCRad (mm)) to light distortion and the simulated projection of the PSF (arcmin) with positive (A) and negative (B) induced defocus of 1.00D in cycloplegia conditions.

5. DISCUSSION

The impact of spherical defocus on psychophysical measures of light distortion was not studied before. In this thesis project we will discuss our results and compare them to others author findings with different purposes. The discussion of the present thesis will be subdivided in topics, as done in the presentation of the results, in order to be easier to be followed by the reader. In the beginning of each topic it will be present a short summary of the most important findings with some guidelines, followed by the discussion of the results in light of the previous results obtained by other authors.

5.1 Visual Acuity

In the present study visual acuity under different (high and low contrast distance visual acuity, low contrast distance visual acuity with positive and negative induced defocus of 1.00D) were compared in non-cycloplegic and cycloplegic conditions for young subjects.

Both binocular and monocular VA were superior to 0.00 LogMAR. The binocular VA was always better than the monocular VA under all conditions. This is in agreement with other studies [163-165] reporting better visual performance with both eyes simultaneously (binocular conditions) instead of one eye (monocular conditions). These results support the binocular summation effect. [163-168]

The differences between both non-cycloplegic and cycloplegic situations were always statistically significant and worse with cycloplegia. Indeed this was already expected since the tropicamide usage not only paralyzes the accommodation but also dilates the pupil as well. This may potentially revealing hyperopic refractive errors as the tonic accommodation is lost, but also because of the increase in higher order aberrations as the pupil dilates. This is evident if we observe that the loss of visual acuity is more important under low contrast (about 1 or 2 lines) when compared with the high contrast (about half line), what suggests a loss of image quality with cycloplegia by diminished contrast sensitivity as low contrast conditions are more sensitive to higher order aberrations. Besides, the smaller HCDVA loss compared with LCDVA loss may be due to the spherical-like HOA interaction with the defocus.

When comparing the HCDVA with the LCDVA we found a difference of 0.17±0.06 LogMAR units, being the HCDVA higher than LCDVA. This is in agreements with other studies reports. [39 76 104] For example, Johnson et al. (1995) [76] found a loss at about 0.20 LogMAR units in

VA when the contrast of letters dropped from 97% to 12%, while studied how luminance, contrast and blur influenced the visual acuity. Li and her coworkers (2009) [39] found 0.80 LogMAR and 0.24 LogMAR units for HCDVA and LCDVA, respectively, with the best distance correction.

Other relevant finding of this study is that both positive and negative induced spherical defocus decreased the LCDVA, such as expected. Under non-cycloplegic conditions the loss on LCDVA was significantly higher with the positive blur, while with the induction of negative defocus the loss is around one letter only, not being significant (see **Table 4.3** in section 4.2). Without cycloplegia this was already expected, since a positive lens relaxes the accommodation while a negative lens stimulates the accommodation. But with cycloplegia both LCDVA with induced defocus worsen similarly, although with positive defocus the LCDVA was still slightly worse than with the negative defocus. This difference between LCDVA with +1.00D and LCDVA with -1.00D with cycloplegia may be explained by the fact that the cycloplegic may not be at its maximum effect, allowing the subjects to slightly accommodate. Johnson et al. (1995) [76] found similar results but they used positive induced blur only. They found a decline at about 0.30 LogMAR in visual acuity of 12% contrast with a induced +1.00D blur in non-cycloplegic conditions, while in our study we found a slightly higher decrease (0.35±0.19 LogMAR) under 10% contrast visual acuity in both non-cycloplegic and cycloplegic conditions. This finding confirms in the this study that low contrast VA is a better predictor of vision quality than the high contrast visual acuity, which might be more relevant at low luminance levels, where contrast sensitivity is more effected by changes in optical quality.

5.2 High Order Aberrations

Ocular wavefront aberrations were measured with and without cycloplegia. Its values were recorded for a mesopic pupil size for each subject and a 5mm pupil without cycloplegia and for 5mm pupil size with cycloplegia. This was because the light distortion measurement were taken with the natural mesopic pupil size of each subject without cycloplegia, and with cycloplegia the pupil size of every subject was limited to 5mm by a diaphragm.

The distribution of HOA was shown to be very variable between the participants. Having in account the standard deviation of total, spherical-like and coma-like HOA RMS the variability is remarkable. This is especially true for COMA and TOTAL HOA RMS without cycloplegia. The three values of HOA RMS values are within the normal range [169], being the Spherical-like HOA slightly positive for all the participants (0,095±0,077µm), but higher than reported by the literature in normal young subjects aged 20 to 29 years old for a 5mm pupil diameter (0,065±0,057µm). [48] However, contrary to the literature in this study the most prominent HOA was the coma-like HOA having higher values than the spherical-like HOA. [7 39 46] In this study we found the RMS values under cycloplegic conditions to be lower than without cycloplegia because the natural mesopic pupil size is slightly higher than the standardized pupil diameter of 5mm with cycloplegia (see Table 4.1 and Table 9.1 from Attachment 2 on appendix). This was already expected since the natural mesopic pupil size was about 0.64mm larger than 5mm and is in agreement with the literature which reports higher HOA RMS values for higher pupil diameter. [48 60 85]

No differences were found between the non-cycloplegic and cycloplegic HOA RMS when considered the same pupil size (5mm), as expected. This means that the measures are very similar and are minimally influenced by accommodation in the non-cycloplegic condition. This is in concordance with Miranda et al. (2009)[170] who found that IRx3 aberrometer is reliable and with a good repeatability. However, in this study some repeatability problems may be due to subjects' fixation errors, micro-fluctuations in accommodation, small eye movements, tear film instability or tear film disorganization due to cycloplegic instillation. All these factors cause changes in the ocular aberrations, affecting more the horizontal and vertical coma.[53] Despite this, these effects seem to have minor impact on the reliability in the context of the present study.

5.3 Light Distortion Analysis

In this section the light distortion results are discussed separately for the comparison between monocular and binocular LDA values, the impact of defocus and the comparison between non-cycloplegic and cycloplegic LDA measures.

5.3.1 Comparison between monocular and binocular measures

Monocular and binocular light distortion measures for size and irregularity parameters were compared in both non-cycloplegic and cycloplegic conditions. According to the results on section 4.4.1, the monocular results of light distortion were always worse than the binocular ones. Our findings suggest an improvement on light distortion perception when under binocular conditions resulting in an attenuation on the binocular light distortion compared to the light distortion obtained for each eye separately, even in healthy eyes. This suggests that there is a neural capacity to reduce the light distortion under binocular conditions, which consequently improves the optical quality, being consistent with other studies showing similar results in post-surgical eyes. [165] In addition to Jiménez et al. (2006) [165] findings, there are clinical experiments [163 164 166-168] demonstrating that in healthy subjects the binocular visual performance is superior to the monocular one and a binocular summation occurs in subjects with similar visual acuities in both eyes and with decreased interocular differences on image quality, particularly at low illumination levels. Plainis et al. (2010) [168] studied the effect of several levels of induced positive defocus on the measurement of the pattern reversal visual evoked potential and on visual acuity. In the context of the binocular summation, they found that binocular vision attenuates the effect of defocus what might be explained by the activation of a major number of neurons at close-to-threshold detection when in binocular stimulation. The effect of binocular summation was already referred on the discussion of the visual acuity results (section 5.1).

Although in general both size and irregularity parameters were worse in monocular than in binocular conditions, we observed that the irregularity parameters of light distortion did not present statistically significant differences between monocular and binocular measures, except under non-cycloplegic conditions. This might suggest that the irregularity of the perceived light distortion might not be significantly changed from monocular to binocular vision due to the interocular wavefront aberration simetry. This might be different in eyes with monocularly assymetric distortions as in corneal ectasic disease, but this needs to be investigated in the future. Overal, the present study suggests that the size of the light distortion is more affected than the irregularity parameters when comparing monocular and binocular vision.

5.3.2 Impact of defocus on light distortion

For the assessment of the impact of defocus on light distortion, we induced a positive and negative defocus of 1.00D over the best distance correction. The device was at 2.00 meters from the subject. However we did not considered the accommodative response of 0.50D for non-cycloplegic conditions once Ferreira-Neves et al. (2015) [136] found no differences between LDA parameters with and without spherical compensation to the measuring distance +0.50D. We compared the results from each situation (no defocus, positive defocus and negative defocus) in cycloplegic conditions, with a limited and standardized pupil size of 5mm. Although it could be expected that the lack of compensation to the examination distance would result in a 0.50 hyperopic defocus that will worsen light distortion, this in fact is not the case. This might be explained by the small accommodative effort that the patient needs to do to compensate for it and that might be even present under tropicamide that allows a small residual accommodation to be performed.

We found the mean best fit circle radius of the distortion/halo to be 14.18±4.19mm and 12.83±3.99mm for monocular and binocular situations, respectively. These results are lower than the ones found by Puell et al. (2013) [156] which found a mean radius of the halo in healthy subjects to be 36.5±28.8mm. Different methodologies used in both studies, the larger and brighter glare stimulus and the limited meridians studied by the instrument used by the other authors, might explain this difference. Furthermore, in their study the sample included older subjects and it is known that age is a predictor of the increased intraocular scattering and consequently increased light distortion. Besides they used a device with a monitor that simulated less real glare conditions than LDA.

In the present study, both positive and negative induced defocus increased the perception of light distortion, particularly its size. This is in agreement with the optical findings of Villegas et al. (2002) [150] which found the double-pass images to have a larger light spread around the central point with different levels of positive and negative induced defocus, increasing with the level of defocus. In addition, Santolaria et al. (2015) [119] found an increase in LDA parameters in subjects undergoing Orto-K after one day of treatment. However, besides the differences on light distortion parameters were not statistically significant between positive and negative defocus, we observed that negative defocus induced a smaller disturbance than the positive one. This might be due to the tropicamide effect not being fully achieved, allowing a small amount of accommodative stimulus (about 0.50D once the device was at 2.00 meters from the subjects) and a partial compensation of the negative defocus. In order to verify this, we simulated the PSF in three cycloplegic conditions (see **Figure 5.1**) with positive and negative levels of defocus. We observed that when subjects are allowed to accommodate (situations 1 and 3 from **Figure 5.1**) we verified that the PSFs obtained with the negative defocuses are more contained in the external part of the PSF than with the positive defocuses. So, the fact that the tropicamide did not reach its maximum effect allowed the subjects to slightly accommodate.

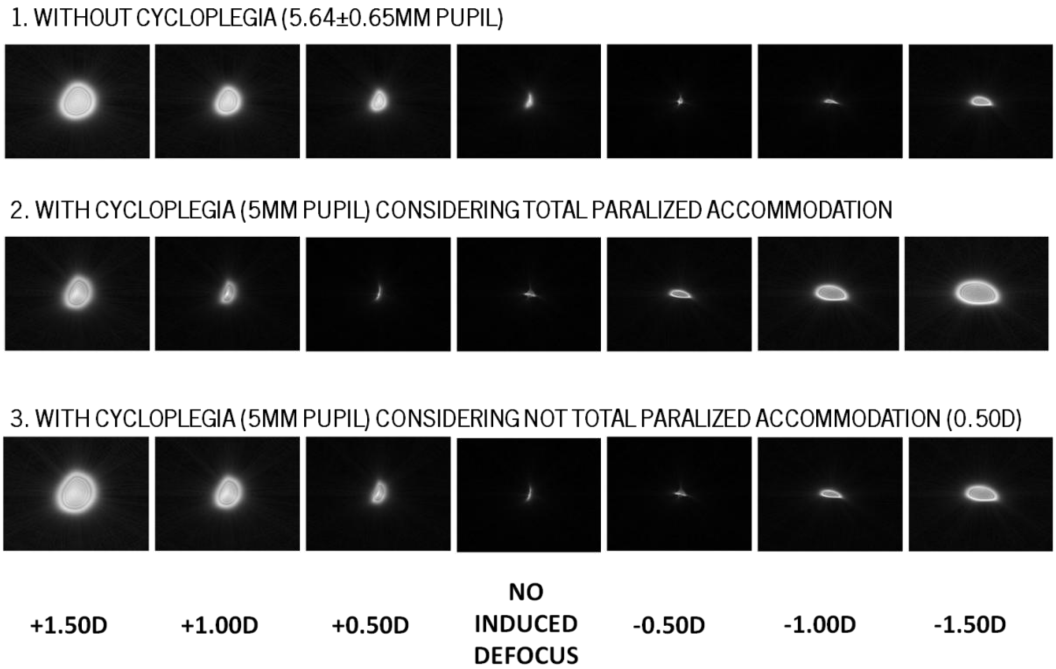


Figure 5.1 Representation of simulated PSFs for different levels of defocus (from +1.50D to -1.50D) in three different cycloplegic situations.

Nevertheless the coupling effect of defocus with the HOA must be also considered. Contrary to our results Cheng et al. (2004) [51] observed visual improvement by adding spherical defocus of the same sign as the spherical-like HOA. However, some studies [35 41 171] reported that the combination between the positive spherical-like HOA and the induction of negative defocus (contrary signs) may improve the visual performance. Cheng et al. (2003) [47] found the negative induced defocus to attenuate the spherical-like HOA effect, producing less positive RMS values of spherical-like HOA. So, the combination between positive spherical-like HOA of the participants of this thesis project and the negative defocus may have produced a lower light disturbance compared with the positive defocus of the same level with a spherical-like HOA of the same sign.

5.3.3 Comparison between non-cycloplegic and cycloplegic measures

We compared the light distortion measures with cycloplegia and without cycloplegia in order to understand the influence of pupil size and aberrations on the size and irregularity of light distortion.

Our results showed that all size and irregularity parameters increased in cycloplegic conditions. On one hand, this is contrary to what we expected once a smaller pupil size and consequently lower values of HOA should produce a smaller perception of light distortion than with a larger pupil size and consequently higher magnitude of HOA. Our findings may be explained by the uncorrected latent hyperopic refractive error as the tonic accommodation is lost, increasing the straylight reaching the retina. However, although LCDVA and light distortion parameters did not show to be correlated in this study, the reduction on LCDVA with cycloplegia is in agreement with the increased light distortion phenomena because both are affected by the increase on HOA magnitude.[3 4 29 35 39 42 46 47]

5.4 Impact of High-Order Aberration on Light Distortion

In this experimental study we also observed the impact and relationship from total (corneal and internal) HOA and light distortion. This analysis was made by correlating the HOA with light distortion parameters without cycloplegia and a 5.64±0.65mm pupil, correlating the changes on light distortion parameters and HOA values with cycloplegia (5mm pupil) and correlating the changes on light distortion parameters with the changes on HOA with cycloplegia.

In the literature are reported correlations of light distortion with corneal HOA. [94 114 119] For example, Villa et al. (2007) [94] found a significantly fair correlation between the halo disturbance index from Starlights v1.0 and the Total, coma and spherical-like RMS of the corneal HOA in subjects before and after LASIK surgery, accompanied by an increase in light distortion with corneal HOA. However, in this study we used the total (corneal and internal) HOA in order to evaluate their correlation with the psychophysical values obtained from LDA parameters.

We found significantly positive fair correlations between size parameters (LDI and BFCRad) of light distortion without cycloplegia and total spherical-like HOA. This suggests that for higher spherical-like HOA RMS the perceived disturbance area would be increased. By another hand, we also found statistically significant positive fair correlations for BFCIrreg parameter with total and coma-like HOA in cycloplegic conditions with no induced defocus, but not for the size parameters as without cycloplegia. These findings suggest that the increasing in total and coma-like HOA RMS decreases the regularity of light distortion. In graphs from **Figure 4.6** we noticed the existence of an outlier. After removal the subject with the highest value of spherical-like HOA the correlation coefficient reduced slightly in some cases but the correlations remained fair and statistically significant so that the conclusions of the work do not change because of this subject with a somewhat atypical behaviour and that seemed, at first glance, to alter the linear correlation coefficient.

The discussion of our results from the comparison of light distortion under non-cycloplegic and cycloplegic conditions and the relationship between total HOA and light distortion would not be complete if we did not pay attention to the role of the pupil. Our results show that the light distortion increased when in cycloplegic conditions, wich in pupil terms represents an increase on light distortion accompainied by a decrease on the pupil size once the non-cycloplegic pupil was larger than the cycloplegic where we limited the dilated pupil size by an artificial diaphragm. Besides when considering the ocular aberrations there is a need to have in account the pupil size. As discussed before we expected light distortion to maintain or decrease with cycloplegia (5mm pupil), but the opposite happened. So our results suggest that despite the association between pupil size and HOA referred in the literature the pupil diameter it is not a significant contributor for light distortion when considered by itself. This is in agreement with other authors findings. [93 94 111 112 114] However, when considering the pupil size associated to HOA these are related to the night visual disturbances.

5.5 Light Distortion and Topographic quality parameters

We measured the corneal asphericity value (Q-value), SRI and SAI in order to understand if there was any relationship between the light distortion perceived by each subjects in natural mesopic conditions (without cycloplegia) and their own topographic quality values.

As it is known, the cornea is the optical element with a major dioptric power contribution to the eye and consequently has a great influence on vision quality, mainly due to the ocular aberrations. [158 172 173] Studies proved that the corneal natural state is not spherical but rather prolate, flattening from its center to the periphery, influencing the corneal spherical ocular aberration.[172] This corneal shape it is called asphericity and it is referred as the Q-value and ranges between -0.03 and -0.33 in normal healthy young eyes. The Q-value can be considered as an optical quality predictor but some authors do not support this statement because the asphericity values obtained by topography have a larger variability than the spherical aberration obtained by aberrometers.[158 172 173] The SRI parameter is a predictor of the optical quality of the central cornea characterized by local fluctuations in corneal power. Its normal values range 0.0 to 0.56. The lower the SRI value, smoother the corneal surface, so increased values correspond to major central corneal irregularity.[159] SRI magnitude is based on a comparative analysis of dioptric powers of adjacent points in 256 hemi-meridians in the 10 central-rings [160], being characterized by the average of the value of its rectilinear neighbors over the central 4mm chord area. The corneal asymmetry with respect to the visual axis is given by the SAI value. Its value is calculated by power differences between corresponding points located 180 degrees apart of the same chord measured in 4 central rings. If the cornea were a perfect sphere, SAI values would be zero and would increase when the corneal power distribution becomes more asymmetrical. Instead, as the cornea is an aspherical prolate surface, SAI normal values ranging between 0.10 and 0.42. This topographic index is sensible to changes in corneal symmetry, which can be very useful in detecting irregular astigmatisms and off-center keratoconus.[159 160]

The values of the topographic parameters (Q, SRI and SAI) in our sample are within the normal range stated by the literature [158-161 173], but SAI has a slightly more positive values. In this study it was not found any relationship between Q and light distortion which suggests that asphericity do not influence the night vision quality. This might be explained by asphericity influence the corneal spherical-like HOA but not the total spherical-like HOA.[172] However this parameter is very important and needs to be considered in refractive surgeries once changes in asphericity induce changes in corneal spherical-like HOA. [166] On the another side, we found moderately strong and significant correlation for SRI and SAI with BFCRad. Our findings are in agreement with Kojima et al. (2010) [120] which found very similar correlation values for SRI ($r=0.52$, $p<0.01$) and SAI ($r=0.41$, $p<0.05$) with glare score after one month of ortokeratology treatment. We also found a fair significant correlation between SAI and BFCIrreg. We did not expect to find this in a normal (non-treated) cornea, but these results might reflect that the instrument used is sensitive to detect minor differences in light distortion even for values of topographical parameters within normal range of non-treated corneas. These findings may suggest that SRI and SAI can be predictors of the visual quality in mesopic conditions, which highlights the corneal irregularity for the assessment of night vision performance in patients with corneal changes by pathologies or refractive treatments. [56 83 84]

5.6 Relationship of Visual Acuity with Light Distortion

We investigated if the losses in low contrast visual acuity were related to the increases in light distortion by comparing their changes with both types of induce defocus with cycloplegia. In fact we found a decrease in LogMAR LCDVA with both positive and negative induced defocus with cycloplegia accompanied by an increase on the perception of light distortion. The decrease on LCDVA and the increase on light distortion with the negative induced defocus were lower than with the positive defocus, which suggest that positive defocus causes more straylight and retinal image disturbance than a negative defocus. However, the correlation between the two variables for both type of induced defocus was poor and non-significant which might propose that LCDVA it is not directly associated to light distortion phenomena. Besides, it is necessary to take into account the sample size which for the visual acuity differences and comparisons with other variables should be larger.

5.7 Light distortion size and PSF

To understand if the optical metric (PSF) was related to the size of the perceived light distortion (psychophysical measure) we compared both values (real values of the BFCRad and simulated values of PSF) for each subject with the two types of defocus used along this project. We found a poor and non-significant between the psychophysical and optical metrics which suggest that the objective estimations of the simulated PSF it was not reflected on the psychophysical measures. However this might be an interesting start-point to analyze this relationship for an extent object instead a punctual one.

6. CONCLUSIONS

From the current study, the following conclusions have been derived:

- The measurement of LCDVA reflects the optical quality of the eye once is affected in cycloplegic condition by the induction of the two types of defocus.

- There is a binocular attenuation of the light distortion compared with the monocular measures in normal healthy eyes. This implies a neural capacity for a binocular summation which produces an improvement on visual quality by decreasing the perception of disturbed light.

- Both types of defocus increased the perceived light distortion compared to no induced defocus measures with cycloplegia. In addition, positive and negative defocus produces a similar light disturbance.

- The increase on total spherical-like HOA was associated to an increase on light distortion size, while coma-like and Total-like HOA were associated to increases in light distortion irregularity.

- The pupil by itself did not affect the light distortion perception but becomes relevant when associated with high-order aberrations.

- The corneal asphericity (Q) did not influence the light distortion in normal healthy subjects. However, SRI and SAI showed to be good predictors of visual quality by correlate with light distortion size.

- Positive and negative induced defocus decrease the visual quality (LCDVA and light distortion) in a similar way. Despite LCDVA showed to be a good predictor of optical quality, it was not correlated with the psychophysical light distortion measures.

- There were no relationship between the psychophysical measure from LDA and the simulated optical metric PSF.

7. FUTURE WORK

- Study the impact of defocus on light distortion with real uncorrected myopes and hyperopes.
- Include a larger sample to evaluate the impact of lower uncorrected spherical and cylindrical refractive errors on light distortion between different levels.
- Assess the influence of accommodation on light distortion.
- Compare the measures of light distortion obtained with LDA and other similar devices.
- Future works can be done with induced and real astigmatic refractive errors non-corrected to assess its impact on light distortion.
- Psychophysical measurement of light distortion should be integrated in pre- and post-surgical evaluation routine in order to evaluate the vision quality before and after the treatment.
- The study of the relationship between the psychophysical and optical metrics should be analyzed more carefully on future works.

8. BIBLIOGRAPHY

1. Piñero DP, Ortiz D, Alio JL. Ocular scattering. Optom Vis Sci 2010;**87**(9):E682-96.

2. Artal P. Optics of the eye and its impact in vision: a tutorial. Advances in Optics and Photonics 2014;**6**(3):27.

3. Marcos S. Image quality of the human eye. Int Ophthalmol Clin 2003;**43**(2):43-62.

4. Wanek JM, Mori M, Shahidi M. Effect of aberrations and scatter on image resolution assessed by adaptive optics retinal section imaging. J Opt Soc Am A Opt Image Sci Vis 2007;**24**(5):1296-304.

5. Thibos LN. The prospects for perfect vision. J Refract Surg 2000;**16**(5):S540-6.

6. Schwiegerling J. Theoretical limits to visual performance. Surv Ophthalmol 2000;**45**(2):139-46.

7. Marcos S. Aberrometry: basic science and clinical applications. Bull Soc Belge Ophtalmol 2006(302):197-213.

8. Hahn DW. Light Scattering Theory. Department of Mechanical and Aerospace Engineering, University of Florida, July 2009.

9. Van de Huslt H. Light Scattering by Small Particles. Mineola, NY: Dover Publications, 1981.

10. Costello MJ, Johnsen S, Gilliland KO, Freel CD, Fowler WC. Predicted light scattering from particles observed in human age-related nuclear cataracts using mie scattering theory. Invest Ophthalmol Vis Sci 2007;**48**(1):303-12.

11. de Waard PW, IJspeert JK, van den Berg TJ, de Jong PT. Intraocular light scattering in age-related cataracts. Invest Ophthalmol Vis Sci 1992;**33**(3):618-25.

12. Mihashi T, Hirohara Y, Bessho K, Maeda N, Oshika T, Fujikado T. Intensity analysis of Hartmann-Shack images in cataractous, keratoconic, and normal eyes to investigate light scattering. Jpn J Ophthalmol 2006;**50**(4):323-33.

13. van den Berg TJ, Hwan BS, Delleman JW. The intraocular straylight function in some hereditary corneal dystrophies. Doc Ophthalmol 1993;**85**(1):13-9.

14. Yamamoto T, Kamei M, Yokoi N, Yasuhara T, Tei M, Kinoshita S. Platelet aggregates in various stages of diabetic retinopathy: evaluation using the particle-counting light-scattering method. Graefes Arch Clin Exp Ophthalmol 2005;**243**(7):665-70.

15. Babizhayev MA, Minasyan H, Richer SP. Cataract halos: a driving hazard in aging populations. Implication of the Halometer DG test for assessment of intraocular light scatter. Appl Ergon 2009;**40**(3):545-53.

16. Ginis HS, Perez GM, Bueno JM, Pennos A, Artal P. Wavelength dependence of the ocular straylight. Invest Ophthalmol Vis Sci 2013;**54**(5):3702-8.

17. Jinabhai A, O'Donnell C, Radhakrishnan H, Nourrit V. Forward light scatter and contrast sensitivity in keratoconic patients. Cont Lens Anterior Eye 2012;**35**(1):22-7.

18. Cabot F, Saad A, McAlinden C, Haddad NM, Grise-Dulac A, Gatinel D. Objective assessment of crystalline lens opacity level by measuring ocular light scattering with a double-pass system. Am J Ophthalmol 2013;**155**(4):629-35, 35.e1-2.

19. Tort AG. Objective Intraocular Scattering Evaluation in cataract patients. Master thesis. Universitat Politècnica de Catalunya, Terrassa - Barcelona, Spain, 2009.

20. van den Berg TJ, Spekreijse H. Light scattering model for donor lenses as a function of depth. Vision Res 1999;**39**(8):1437-45.

21. Hart RW, Farrell RA. Light scattering in the cornea. J Opt Soc Am 1969;**59**(6):766-74.

22. Cox MJ, Atchison DA, Scott DH. Scatter and its implications for the measurement of optical image quality in human eyes. Optom Vis Sci 2003;**80**(1):58-68.

23. van den Berg TJ, Franssen L, Kruijt B, Coppens JE. History of ocular straylight measurement: A review. Z Med Phys 2013;**23**(1):6-20.

24. Patel SV, Winter EJ, McLaren JW, Bourne WM. Objective measurement of backscattered light from the anterior and posterior cornea in vivo. Invest Ophthalmol Vis Sci 2007;**48**(1):166-72.

25. van den Berg TJTP, van Rijn RLJ, Vonhoff DJ, et al. Disability glare in the Aging Eye. Assessment and Impact on Driving: J Optom, 2009:112-18.

26. Aslam TM, Haider D, Murray IJ. Principles of disability glare measurement: an ophthalmological perspective. Acta Ophthalmol Scand 2007;**85**(4):354-60.

27. Siew EL, Opalecky D, Bettelheim FA. Light scattering of normal human lens. II. Age dependence of the light scattering parameters. Exp Eye Res 1981;**33**(6):603-14.

28. McAlinden C, McCartney M, Moore J. Mathematics of Zernike polynomials: a review. Clin Experiment Ophthalmol 2011;**39**(8):820-7.

29. Applegate RA, Ballentine C, Gross H, Sarver EJ, Sarver CA. Visual acuity as a function of Zernike mode and level of root mean square error. Optom Vis Sci 2003;**80**(2):97-105.

30. Maeda N. Clinical applications of wavefront aberrometry - a review. Clin Experiment Ophthalmol 2009;**37**(1):118-29.

31. Thibos LN, Applegate RA, Schwiegerling JT, Webb R, applications VSTMVsai. Standards for reporting the optical aberrations of eyes. J Refract Surg 2002;**18**(5):S652-60.

32. (ISO) IOfS. Ophthalmic Optics and Instruments – Reporting Aberrations of the Human Eye Geneva, Switzerland: ISO, 2008.

33. Lombardo M, Lombardo G. Wave aberration of human eyes and new descriptors of image optical quality and visual performance. J Cataract Refract Surg 2010;**36**(2):313-31.

34. Atchison D, Scott D, Cox M. Mathematical treatment of ocular aberrations: a user's guide. In: Lakshminarayanan V, ed, OSA Trends in Optics and Photonics, vol. 35. Vision Science and Its Applications. Washington DC, : Optical Society of America 2000:110–30.

35. Applegate RA, Marsack JD, Ramos R, Sarver EJ. Interaction between aberrations to improve or reduce visual performance. J Cataract Refract Surg 2003;**29**(8):1487-95.

36. Specialistica L. Phase Diversity Phase Retrieval in ottica adattiva. In: Capraro I, Naletto G, eds. Italy: Università degli Studi Di Padova - Facoltà di Ingegneria, 2010.

37. Rossi EA, Weiser P, Tarrant J, Roorda A. Visual performance in emmetropia and low myopia after correction of high-order aberrations. J Vis 2007;**7**(8):14.

38. Lombardo M, Serrao S, Devaney N, Parravano M, Lombardo G. Adaptive optics technology for high-resolution retinal imaging. Sensors (Basel) 2013;**13**(1):334-66.

39. Li J, Xiong Y, Wang N, et al. Effects of spherical aberration on visual acuity at different contrasts. J Cataract Refract Surg 2009;**35**(8):1389-95.

40. Marcos S, Velasco-Ocana M, Dorronsoro C, Sawides L, Hernandez M, Marin G. Impact of astigmatism and high-order aberrations on subjective best focus. J Vis 2015;**15**(11):4.

41. Cheng X, Bradley A, Ravikumar S, Thibos LN. Visual impact of Zernike and Seidel forms of monochromatic aberrations. Optom Vis Sci 2010;**87**(5):300-12.

42. Bakaraju RC, Ehrmann K, Ho A, Papas E. Inherent ocular spherical aberration and multifocal contact lens optical performance. Optom Vis Sci 2010;**87**(12):1009-22.

43. Yoon G, Jeong TM, Cox IG, Williams DR. Vision improvement by correcting higher-order aberrations with phase plates in normal eyes. J Refract Surg 2004;**20**(5):S523-7.

44. Oliveira CM, Ferreira A, Franco S. Wavefront analysis and Zernike polynomial decomposition for evaluation of corneal optical quality. J Cataract Refract Surg 2012;**38**(2):343-56.

45. Kelly JE, Mihashi T, Howland HC. Compensation of corneal horizontal/vertical astigmatism, lateral coma, and spherical aberration by internal optics of the eye. J Vis 2004;**4**(4):262-71.

46. Kingston AC, Cox IG. Population spherical aberration: associations with ametropia, age, corneal curvature, and image quality. Clin Ophthalmol 2013;**7**:933-8.

47. Cheng X, Bradley A, Hong X, Thibos LN. Relationship between refractive error and monochromatic aberrations of the eye. Optom Vis Sci 2003;**80**(1):43-9.

48. Applegate RA, Donnelly WJ, Marsack JD, Koenig DE, Pesudovs K. Three-dimensional relationship between high-order root-mean-square wavefront error, pupil diameter, and aging. J Opt Soc Am A Opt Image Sci Vis 2007;**24**(3):578-87.

49. McLellan JS, Marcos S, Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. Invest Ophthalmol Vis Sci 2001;**42**(6):1390-5.

50. He JC, Burns SA, Marcos S. Monochromatic aberrations in the accommodated human eye. Vision Res 2000;**40**(1):41-8.

51. Cheng H, Barnett JK, Vilupuru AS, et al. A population study on changes in wave aberrations with accommodation. J Vis 2004;**4**(4):272-80.

52. Montés-Micó R, Cáliz A, Alió JL. Wavefront analysis of higher order aberrations in dry eye patients. J Refract Surg 2004;**20**(3):243-7.

53. Efron S, Efron N, Morgan PB. Repeatability and reliability of ocular aberration measurements in contact lens wear. Cont Lens Anterior Eye 2008;**31**(2):81-8.

54. Jinabhai A, Radhakrishnan H, O'Donnell C. Repeatability of ocular aberration measurements in patients with keratoconus. Ophthalmic Physiol Opt 2011;**31**(6):588-94.

55. Oie Y, Maeda N, Kosaki R, et al. Characteristics of ocular higher-order aberrations in patients with pellucid marginal corneal degeneration. J Cataract Refract Surg 2008;**34**(11):1928-34.

56. Oshika T, Tokunaga T, Samejima T, Miyata K, Kawana K, Kaji Y. Influence of pupil diameter on the relation between ocular higher-order aberration and contrast sensitivity after laser in situ keratomileusis. Invest Ophthalmol Vis Sci 2006;**47**(4):1334-8.

57. Berntsen DA, Barr JT, Mitchell GL. The effect of overnight contact lens corneal reshaping on higher-order aberrations and best-corrected visual acuity. Optom Vis Sci 2005;**82**(6):490-7.

58. Wang L, Santaella RM, Booth M, Koch DD. Higher-order aberrations from the internal optics of the eye. J Cataract Refract Surg 2005;**31**(8):1512-9.

59. Guirao A, Williams DR. A method to predict refractive errors from wave aberration data. Optom Vis Sci 2003;**80**(1):36-42.

60. Mello GR, Rocha KM, Santhiago MR, Smadja D, Krueger RR. Applications of wavefront technology. J Cataract Refract Surg 2012;**38**(9):1671-83.

61. Thibos LN, Hong X, Bradley A, Applegate RA. Accuracy and precision of objective refraction from wavefront aberrations. J Vis 2004;**4**(4):329-51.

62. Tuan KM, Chernyak D, Feldman ST. Predicting patients' night vision complaints with wavefront technology. Am J Ophthalmol 2006;**141**(1):1-6.

63. van den Berg TJ, Franssen L, Coppens JE. Straylight in the human eye: testing objectivity and optical character of the psychophysical measurement. Ophthalmic Physiol Opt 2009;**29**(3):345-50.

64. Marcos S. Aberrations and visual performance following standard laser vision correction. J Refract Surg 2001;**17**(5):S596-601

65. Mainster MA, Turner PL. Multifocal IOLs and Maculopathy - How much is too much? In: Chang DF, ed. Mastering Refractive IOLs: The Art and Science. Thorofare, NJ, USA: SLACK Incorporated, 2008:391.

66. Lombardo M, Lombardo G. New methods and techniques for sensing the wave aberrations of human eyes. Clin Exp Optom 2009;**92**(3):176-86.

67. Thibos LN, Hong X. Clinical applications of the Shack-Hartmann aberrometer. Optom Vis Sci 1999;**76**(12):817-25.

68. Díaz-Doutón F, Benito A, Pujol J, Arjona M, Güell JL, Artal P. Comparison of the retinal image quality with a Hartmann-Shack wavefront sensor and a double-pass instrument. Invest Ophthalmol Vis Sci 2006;**47**(4):1710-6.

69. Franssen L, Coppens JE, van den Berg TJ. Compensation comparison method for assessment of retinal straylight. Invest Ophthalmol Vis Sci 2006;**47**(2):768-76.

70. Artal P, Benito A, Pérez GM, et al. An objective scatter index based on double-pass retinal images of a point source to classify cataracts. PLoS One 2011;**6**(2):e16823.

71. van Bree MC, van Verre HP, Devreese MT, Larminier F, van den Berg TJ. Straylight values after refractive surgery: screening for ocular fitness in demanding professions. Ophthalmology 2011;**118**(5):945-53.

72. Tunnacliffe AH. *Introduction to Visual Optics*. 4th Edition ed. Andover, Hampshire, England: TJ Reproductions, 1993.

73. Green M. Night Vision. Secondary Night Vision 2013.

74. Wood JM, Collins MJ, Chaparro A, et al. Differential effects of refractive blur on day and nighttime driving performance. Invest Ophthalmol Vis Sci 2014;**55**(4):2284-9.

75. Wood J, Chaparro A, Carberry T, Chu BS. Effect of simulated visual impairment on nighttime driving performance. Optom Vis Sci 2010;**87**(6):379-86.

76. Johnson CA, Casson EJ. Effects of luminance, contrast, and blur on visual acuity. Optom Vis Sci 1995;**72**(12):864-9.

77. Simpson TL, Barbeito R, Bedell HE. The effect of optical blur on visual acuity for targets of different luminances. Ophthalmic Physiol Opt 1986;**6**(3):279-81.

78. Stiles WS, Crawford BH. The Luminous Efficiency of Rays Entering the Eye Pupil at Different Points. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character*. Royal Society, Mar. 2, 1933:pp. 428-50.

79. Legge GE, Mullen KT, Woo GC, Campbell FW. Tolerance to visual defocus. J Opt Soc Am A 1987;**4**(5):851-63.

80. Charman WN, Jennings JA, Whitefoot H. The refraction of the eye in the relation to spherical aberration and pupil size. Br J Physiol Opt 1978;**32**:78-93.

81. Atchison DA, Scott DH. Contrast sensitivity and the Stiles–Crawford effect. Vision Res 2002;**42**(12):1559-69.

82. Castro JJ, Ortiz C, Pozo AM, Anera RG, Soler M. A visual test based on a freeware software for quantifying and displaying night-vision disturbances: study in subjects after alcohol consumption. Theor Biol Med Model 2014;**11 Suppl 1**:S1.

83. Franssen L, Tabernero J, Coppens JE, van den Berg TJ. Pupil size and retinal straylight in the normal eye. Invest Ophthalmol Vis Sci 2007;**48**(5):2375-82.

84. Helgesen A, Hjortdal J, Ehlers N. Pupil size and night vision disturbances after LASIK for myopia. Acta Ophthalmol Scand 2004;**82**(4):454-60.

85. Queirós A, Villa-Collar C, González-Méijome JM, Jorge J, Gutiérrez AR. Effect of pupil size on corneal aberrations before and after standard laser in situ keratomileusis, custom laser in situ keratomileusis, and corneal refractive therapy. Am J Ophthalmol 2010;**150**(1):97-109.e1.

86. Jiménez JR, Ortiz C, Pérez-Ocón F, Castro JJ. Objective and subjective optical-quality measurements in subjects with keratitis and age-related macular degeneration Journal of Modern Optics, 2008:55:15,2371-80.

87. Fan-Paul NI, Li J, Miller JS, Florakis GJ. Night vision disturbances after corneal refractive surgery. Surv Ophthalmol 2002;**47**(6):533-46.

88. Jabbur NS, Sakatani K, O'Brien TP. Survey of complications and recommendations for management in dissatisfied patients seeking a consultation after refractive surgery. J Cataract Refract Surg 2004;**30**(9):1867-74.

89. Chu BS, Wood JM, Collins MJ. The effect of presbyopic vision corrections on nighttime driving performance. Invest Ophthalmol Vis Sci 2010;**51**(9):4861-6.

90. Kohnen T, Bühren J, Kasper T, Terzi E. Quality of Vision After Refractive Surgery. In: Kohnen T, Koch DD, eds. Cataract and Refractive Surgery: Springer Berlin Heidelberg, 2005:pp 303-14.

91. McAlinden C, Pesudovs K, Moore JE. The development of an instrument to measure quality of vision: the Quality of Vision (QoV) questionnaire. Invest Ophthalmol Vis Sci 2010;**51**(11):5537-45.

92. Rosen ES. Night vision disturbance. J Cataract Refract Surg 2005;**31**(2):247-9.

93. Klyce SD. Night vision disturbances after refractive surgery: haloes are not just for angels. Br J Ophthalmol 2007;**91**(8):992-3.

94. Villa C, Gutiérrez R, Jiménez JR, González-Méijome JM. Night vision disturbances after successful LASIK surgery. Br J Ophthalmol 2007;**91**(8):1031-7.

95. Pop M, Payette Y. Risk factors for night vision complaints after LASIK for myopia. Ophthalmology 2004;**111**(1):3-10.

96. Gutiérrez R, Jiménez JR, Villa C, Valverde JA, Anera RG. Simple device for quantifying the influence of halos after lasik surgery. J Biomed Opt 2003;**8**(4):663-7.

97. Lackner B, Pieh S, Schmidinger G, et al. Glare and halo phenomena after laser in situ keratomileusis. J Cataract Refract Surg 2003;**29**(3):444-50.

98. Navarro R. The Optical Design of the Human Eye: a Critical Review. J Optom 2009;**2**:16.

99. Michael R, van Rijn LJ, van den Berg TJ, et al. Association of lens opacities, intraocular straylight, contrast sensitivity and visual acuity in European drivers. Acta Ophthalmol 2009;**87**(6):666-71.

100. Lee SS, Wood JM, Black AA. Blur, eye movements and performance on a driving visual recognition slide test. Ophthalmic Physiol Opt 2015;**35**(5):522-9.

101. Schallhorn SC, Tanzer DJ, Kaupp SE, Brown M, Malady SE. Comparison of night driving performance after wavefront-guided and conventional LASIK for moderate myopia. Ophthalmology 2009;**116**(4):702-9.

102. Ortiz C, Castro JJ, Alarcón A, Soler M, Anera RG. Quantifying age-related differences in visual-discrimination capacity: drivers with and without visual impairment. Appl Ergon 2013;**44**(4):523-31.

103. Cohen Y, Zadok D, Barkana Y, et al. Relationship between night myopia and night-time motor vehicle accidents. Acta Ophthalmol Scand 2007;**85**(4):367-70.

104. Wood J, Chaparro A, Hickson L. Interaction between visual status, driver age and distracters on daytime driving performance. Vision Res 2009;**49**(17):2225-31.

105. Palomo-Álvarez C, Puell MC. Capacity of straylight and disk halo size to diagnose cataract. J Cataract Refract Surg 2015;**41**(10):2069-74.

106. Castro JJ, Jiménez JR, Ortiz C, Alarcón A, Anera RG. New testing software for quantifying discrimination capacity in subjects with ocular pathologies. J Biomed Opt 2011;**16**(1):015001.

107. Jiménez JR, Ortiz C, Pérez-Ocón F, Jiménez R. Optical image quality and visual performance for patients with keratitis. Cornea 2009;**28**(7):783-8.

108. Bailey IL, Bullimore MA. A new test for the evaluation of disability glare. Optom Vis Sci 1991;**68**(12):911-7.

109. Elliott DB, Fonn D, Flanagan J, Doughty M. Relative sensitivity of clinical tests to hydrophilic lens-induced corneal thickness changes. Optom Vis Sci 1993;**70**(12):1044-8.

110. Alió JL, Piñero D, Muftuoglu O. Corneal wavefront-guided retreatments for significant night vision symptoms after myopic laser refractive surgery. Am J Ophthalmol 2008;**145**(1):65-74.

111. Cerviño A, Villa-Collar C, Gonzalez-Meijome JM, Ferrer-Blasco T, García-Lázaro S. Retinal straylight and light distortion phenomena in normal and post-LASIK eyes. Graefes Arch Clin Exp Ophthalmol 2011;**249**(10):1561-6.

112. Klyce SD. Night vision after LASIK: the pupil proclaims innocence. Ophthalmology 2004;**111**(1):1-2.

113. Yamane N, Miyata K, Samejima T, et al. Ocular higher-order aberrations and contrast sensitivity after conventional laser in situ keratomileusis. Invest Ophthalmol Vis Sci 2004;**45**(11):3986-90.

114. Villa C, Gutiérrez R, Jiménez J, González-Méijome J. Objective Evaluation of Night Visual Distortion. *European Ophthalmic Review*, 2007:45-7.

115. Anera RG, Villa C, Jiménez JR, Gutierrez R. Effect of LASIK and contact lens corneal refractive therapy on higher order aberrations and contrast sensitivity function. J Refract Surg 2009;**25**(3):277-84.

116. Oliver KM, Hemenger RP, Corbett MC, et al. Corneal optical aberrations induced by photorefractive keratectomy. J Refract Surg 1997;**13**(3):246-54.

117. Martínez CE, Applegate RA, Klyce SD, McDonald MB, Medina JP, Howland HC. Effect of pupillary dilation on corneal optical aberrations after photorefractive keratectomy. Arch Ophthalmol 1998;**116**(8):1053-62.

118. Santolaria E, Cerviño A, Queirós A, Brautaset R, González-Méijome JM. Subjective satisfaction in long-term orthokeratology patients. Eye Contact Lens 2013;**39**(6):388-93.

119. Santolaria Sanz E, Cerviño A, Queirós A, Villa-Collar C, Lopes-Ferreira D, González-Méijome J. Short-Term Changes in Light Distortion in Orthokeratology Subjects BioMed Research International, 2015:7 pages.

120. Kojima T, Hasegawa A, Hara S, et al. Quantitative evaluation of night vision and correlation of refractive and topographical parameters with glare after orthokeratology. Graefes Arch Clin Exp Ophthalmol 2011;**249**(10):1519-26.

121. Kohnen T, Mahmoud K, Bühren J. Comparison of corneal higher-order aberrations induced by myopic and hyperopic LASIK. Ophthalmology 2005;**112**(10):1692.

122. Reinstein DZ, Archer TJ, Gobbe M. Is topography-guided ablation profile centered on the corneal vertex better than wavefront-guided ablation profile centered on the entrance pupil? J Refract Surg 2012;**28**(2):139-43.

123. Lim DH, Lyu IJ, Choi SH, Chung ES, Chung TY. Risk factors associated with night vision disturbances after phakic intraocular lens implantation. Am J Ophthalmol 2014;**157**(1):135-41.e1.

124. Sheppard AL, Shah S, Bhatt U, Bhogal G, Wolffsohn JS. Visual outcomes and subjective experience after bilateral implantation of a new diffractive trifocal intraocular lens. J Cataract Refract Surg 2013;**39**(3):343-9.

125. Vega F, Alba-Bueno F, Millán MS, Varón C, Gil MA, Buil JA. Halo and Through-Focus Performance of Four Diffractive Multifocal Intraocular Lenses. Invest Ophthalmol Vis Sci 2015;**56**(6):3967-75.

126. Schmitz S, Dick HB, Krummenauer F, Schwenn O, Krist R. Contrast sensitivity and glare disability by halogen light after monofocal and multifocal lens implantation. Br J Ophthalmol 2000;**84**(10):1109-12.

127. Allen R, Ho-Yen GO, Beckingsale AB, Fitzke FW, Sciscio AG, Saleh GM. Post-capsulotomy dysphotopsia in monofocal versus multifocal lenses. Clin Exp Optom 2009;**92**(2):104-9.

128. Pieh S, Lackner B, Hanselmayer G, et al. Halo size under distance and near conditions in refractive multifocal intraocular lenses. Br J Ophthalmol 2001;**85**(7):816-21.

129. Brito P, Salgado-Borges J, Neves H, Gonzalez-Meijome J, Monteiro M. Light-distortion analysis as a possible indicator of visual quality after refractive lens exchange with diffractive multifocal intraocular lenses. J Cataract Refract Surg 2015;**41**(3):613-22.

130. Schallhorn S, Tanzer D, Sanders DR, Sanders M, Brown M, Kaupp SE. Night driving simulation in a randomized prospective comparison of Visian toric implantable collamer lens and conventional PRK for moderate to high myopic astigmatism. J Refract Surg 2010;**26**(5):321-6.

131. Hayashi K, Hirata A, Yoshida M, Yoshimura K, Hayashi H. Long-term effect of surface light scattering and glistenings of intraocular lenses on visual function. Am J Ophthalmol 2012;**154**(2):240-51.e2.

132. Vilaseca M, Peris E, Pujol J, Borras R, Arjona M. Intra- and intersession repeatability of a double-pass instrument. Optom Vis Sci 2010;**87**(9):675-81.

133. Drum B, Calogero D, Rorer E. Assessment of visual performance in the evaluation of new medical products. Drug Discov Today Technol 2007;**4**(2):55-61.

134. Michael R, Barraquer R, Rodríguez J, et al. Intraocular straylight screening in medical testing centres for driver licence holders in Spain J Optom.: Elsevier España, 2010:107-14.

135. Linhares JMM, Neves H, Lopes-Ferreira D, Faria-Ribeiro M, Peixoto-de-Matos S, González-Méijome J. Radiometric characterization of a novel LED array system for visual assessment Journal of Modern Optics, 2013:1136-44.

136. Ferreira-Neves H, Macedo-de-Araújo R, Rico-Del-Viejo L, da-Silva AC, Queirós A, González-Méijome JM. Validation of a method to measure light distortion surrounding a source of glare. J Biomed Opt 2015;**20**(7):75002.

137. Buckhurst PJ, Naroo SA, Davies LN, et al. Tablet App halometer for the assessment of dysphotopsia. J Cataract Refract Surg 2015;**41**(11):2424-9.

138. Meikies D, van der Mooren M, Terwee T, Guthoff RF, Stachs O. Rostock Glare Perimeter: a distinctive method for quantification of glare. Optom Vis Sci 2013;**90**(10):1143-8.

139. Maini R, Keeffe J, Weih LA, McCarty CA, Taylor HR. Correction of refractive error in the Victorian population: the feasibility of "off the shelf" spectacles. Br J Ophthalmol 2001;**85**(11):1283-6.

140. Klein R, Klein BE, Linton KL, De Mets DL. The Beaver Dam Eye Study: visual acuity. Ophthalmology 1991;**98**(8):1310-5.

141. Tielsch JM, Sommer A, Witt K, Katz J, Royall RM. Blindness and visual impairment in an American urban population. The Baltimore Eye Survey. Arch Ophthalmol 1990;**108**(2):286-90.

142. Attebo K, Mitchell P, Smith W. Visual acuity and the causes of visual loss in Australia. The Blue Mountains Eye Study. Ophthalmology 1996;**103**(3):357-64.

143. Thibos L, Bradley A. Modeling the Refractive and Neuro-Sensor Systems of the Eye VISUAL INSTRUMENTATION: Optical Design and Engineering Principles Mcgraw-Hill, Inc., New York, 1999:101-59.

144. Bulson RC, Ciuffreda KJ, Hayes J, Ludlam DP. Effect of retinal defocus on basketball free throw shooting performance. Clin Exp Optom 2015;**98**(4):330-4.

145. Chung ST, Jarvis SH, Cheung SH. The effect of dioptric blur on reading performance. Vision Res 2007;**47**(12):1584-94.

146. Llorente L, Barbero S, Cano D, Dorronsoro C, Marcos S. Myopic versus hyperopic eyes: axial length, corneal shape and optical aberrations. J Vis 2004;**4**(4):288-98.

147. Thibos LN, Bradley A, Hong X. A statistical model of the aberration structure of normal, well-corrected eyes. Ophthalmic Physiol Opt 2002;**22**(5):427-33.

148. Collins MJ, Wildsoet CF, Atchison DA. Monochromatic aberrations and myopia. Vision Res 1995;**35**(9):1157-63.

149. MARCOS S, MORENO-BARRIUSO E, LLORENTE L, NAVARRO R, BARBERO S. Do myopic eyes suffer from larger amount of aberrations? Presented at the Myopia 200. Proceedings of the 8th International Conference on Myopia, Boston, 2000.

150. Villegas EA, González C, Bourdoncle B, Bonnin T, Artal P. Correlation between optical and psychophysical parameters as a function of defocus. Optom Vis Sci 2002;**79**(1):60-7.

151. Smith G. Relation between spherical refractive error and visual acuity. Optom Vis Sci 1991;**68**(8):591-8.

152. Atchison D, Smith G, Efron N. The effect of pupil size on visual acuity in uncorrected and corrected myopia. Am J Optom Physiol Opt. , 1979 May:315-23.

153. Poulere E, Moschandreas J, Kontadakis GA, Pallikaris IG, Plainis S. Effect of blur and subsequent adaptation on visual acuity using letter and Landolt C charts: differences between emmetropes and myopes. Ophthalmic Physiol Opt 2013;**33**(2):130-7.

154. Rabin J. Optical defocus: differential effects on size and contrast letter recognition thresholds. Invest Ophthalmol Vis Sci 1994;**35**(2):646-8.

155. Venkataraman AP, Winter S, Unsbo P, Lundström L. Blur adaptation: contrast sensitivity changes and stimulus extent. Vision Res 2015;**110**(Pt A):100-6.

156. Puell MC, Pérez-Carrasco MJ, Barrio A, Antona B, Palomo-Alvarez C. Normal values for the size of a halo produced by a glare source. J Refract Surg 2013;**29**(9):618-22.

157. Amorim-de-Sousa A, Queirós-Pereira A, Macedo-de-Araújo R, Ferreira-Neves H, Rico-del-Viejo L, González-Méijome J. Sensiblidad al desenfoque esferico y astigmático en un nuevo dispositivo para la determinación rápida de la distorsión luminosa. 24 Congreso Internacional de Optometría, Contactología y Óptica Oftálmica: OPTOM 2016, Madrid, 2016.

158. He JC. Theoretical model of the contributions of corneal asphericity and anterior chamber depth to peripheral wavefront aberrations. Ophthalmic Physiol Opt 2014;**34**(3):321-30.

159. Burns DM, Johnston FM, Frazer DG, Patterson C, Jackson AJ. Keratoconus: an analysis of corneal asymmetry. Br J Ophthalmol 2004;**88**(10):1252-5.

160. Wilson SE, Klyce SD. Advances in the analysis of corneal topography. Surv Ophthalmol 1991;**35**(4):269-77.

161. Salmon TO, Horner DG. Comparison of elevation, curvature, and power descriptors for corneal topographic mapping. Optom Vis Sci 1995;**72**(11):800-8.

162. Chan YH. Biostatistics 104: correlational analysis. Singapore Med J 2003;**44**(12):614-9.

163. Cagenello R, Arditi A, Halpern DL. Binocular enhancement of visual acuity. J Opt Soc Am A Opt Image Sci Vis 1993;**10**(8):1841-8.

164. Azen SP, Varma R, Preston-Martin S, Ying-Lai M, Globe D, Hahn S. Binocular visual acuity summation and inhibition in an ocular epidemiological study: the Los Angeles Latino Eye Study. Invest Ophthalmol Vis Sci 2002;**43**(6):1742-8.

165. Jiménez JR, Villa C, Anera RG, Gutiérrez R, del Barco LJ. Binocular visual performance after LASIK. J Refract Surg 2006;**22**(7):679-88.

166. Villa C, Jiménez JR, Anera RG, Gutiérrez R, Hita E. Visual performance after LASIK for a Q-optimized and a standard ablation algorithm. Appl Opt 2009;**48**(30):5741-7.

167. Vandermeer G, Rio D, Gicquel JJ, Pisella PJ, Legras R. Subjective through-focus quality of vision with various versions of modified monovision. Br J Ophthalmol 2015;**99**(7):997-1003.

168. Plainis S, Petratou D, Giannakopoulou T, Atchison DA, Tsilimbaris MK. Binocular summation improves performance to defocus-induced blur. Invest Ophthalmol Vis Sci 2011;**52**(5):2784-9.

169. Salmon TO, Thibos LN, Bradley A. Comparison of the eye's wave-front aberration measured psychophysically and with the Shack-Hartmann wave-front sensor. J Opt Soc Am A Opt Image Sci Vis 1998;**15**(9):2457-65.

170. Miranda MA, O'Donnell C, Radhakrishnan H. Repeatability of corneal and ocular aberration measurements and changes in aberrations over one week. Clin Exp Optom 2009;**92**(3):253-66.

171. Cheng X, Bradley A, Thibos LN. Predicting subjective judgment of best focus with objective image quality metrics. J Vis 2004;**4**(4):310-21.

172. Fuller DG, Alperin D. Variations in corneal asphericity (Q value) between African-Americans and whites. Optom Vis Sci 2013;**90**(7):667-73.

173. Pérez-Escudero A, Dorronsoro C, Marcos S. Correlation between radius and asphericity in surfaces fitted by conics. J Opt Soc Am A Opt Image Sci Vis 2010;**27**(7):1541-8

9. APPENDIX

Attachment 1 Consent Form signed by every participant in this thesis project.

Voluntário: ___

"Impact of Defocus in the Measurement of Light Distortion: Simulation and Experimental Measurements"
Universidade do Minho

DOCUMENTO DE CONSENTIMENTO INFORMADO

O presente documento visa informá-lo acerca dos objetivos, métodos, benefícios previstos e potenciais riscos inerentes ao estudo para o qual se está a voluntariar, intitulado **"Impact of Defocus in the Measurement of Light Distortion: Simulation and Experimental Measurements"**.

O presente documento e os procedimentos a que diz respeito, respeitam a "Declaração de Helsínquia" da Associação Médica Mundial (Helsínquia 1964; Tóquio 1975; Veneza 1983; Hong Kong 1989; Somerset West 1996 e Edimburgo 2000, Seul
2008).

Hoje em dia, mais importante do que ter uma boa acuidade visual é ter uma boa qualidade e performance visual. O sistema visual humano não é um sistema ótico perfeito, sendo que a qualidade visual pode ser afetada por ametropias não corrigidas, por aberrações oculares intrínsecas a cada sujeito e por alterações na transparência dos componentes óticos do olho.

Com o aumento de sujeitos que recorrem a cirurgias refrativas para descartarem o uso de óculos e com a perda de transparência dos meios óticos do olho, as queixas de diminuição da qualidade visual têm sido cada vez mais frequentes, principalmente em condições de baixa iluminação (como por exemplo, na condução durante a noite). As principais queixas são o encandeamento, que gera fenómenos de distorção luminosa, como os halos e o *starburst* à volta de uma fonte de luz forte. Estes fenómenos podem dificultar tarefas como o reconhecimento de pessoas, sinais de trânsito, carros, etc… principalmente em condições de baixa iluminação. Por vezes, a visão desfocada provocada por ametropias não corrigidas podem ser as responsáveis por estas distorções luminosas.

Desta forma, este projeto tem como objetivo saber de que forma o desfocado provocado pela incorreção das ametropias e as aberrações oculares influenciam a distorção luminosa à volta de uma fonte de luz de *glare* em condições de iluminação reduzida.

Para a recolha dos dados necessários à continuação deste projeto, todo o procedimento tem a duração de cerca de 1 hora. Será avaliada a qualidade visual através de alguns exames não invasivos e será necessária a colocação de uma solução tópica ocular cicloplégica. O cicloplégico é um colírio que permite dilatar a pupila e paralisar a atividade acomodativa durante 2 horas. Neste período de tempo a visão em atividades de perto não será nítida. Uma vez que este fármaco é um dilatador pupilar, é normal que haja uma hipersensibilidade à luz exagerada, sendo recomendado o uso de óculos de sol. Enquanto o efeito não passar o sujeito não deverá conduzir. Segundo o INFARMED, este medicamento poderá ter os seguintes efeitos secundários indesejáveis:

Voluntário: ___

"Impact of Defocus in the Measurement of Light Distortion: Simulation and Experimental Measurements"
Universidade do Minho

-Aumento da pressão intraocular.

-Perturbações psicológicas e comportamentais e outras reações sistémicas já reportadas em crianças.

-Sensação passageira de picadas, secura bucal, dilatação prolongada da pupila dificultando a visão, fotofobia, taquicardia, cefaleia, estimulação parassimpática ou ainda reações alérgicas.

Notas:
-É importante que informa o investigador se notar qualquer alteração repentina de conforto ou aparência dos seus olhos ou se notar que a visão piora rapidamente;

-Os riscos destas complicações podem reduzir-se se cumprir todas as indicações dadas pelo investigador.

Voluntário: ___

"Impact of Defocus in the Measurement of Light Distortion: Simulation and Experimental Measurements"
Universidade do Minho

Declaração de conformidade

Coloque as iniciais do seu 1º e último nome à frente de cada afirmação se concordar com a mesma

O paciente declara que lhe foi prestada informação adequada e foi igualmente dada oportunidade de colocar qualquer questão, tendo sida respondida de modo satisfatório.	
Entendo que é importante para a minha saúde e para o bom desenvolvimento do projeto seguir as instruções dadas pelo investigador principal.	
Compreendo que posso recusar a qualquer momento a continuidade da minha participação no estudo. A recusa em participar ou posterior abandono não prejudicarão a sua relação com a equipa de clínicos ou investigadores.	
Concordo em que os dados obtidos sejam utilizados de forma anónima com os fins científicos ou académicos que a equipa investigadora considerar apropriados.	

Braga,_______de____________________de _______

O paciente: ____________________________ Assinatura:

O investigador: Ana Isabel Carvalho Amorim de Sousa Assinatura:

Contactos Investigador principal: Ana Isabel Carvalho Amorim de Sousa
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Este documento é composto por 3 páginas e feito em duplicado: uma via para o/a investigador/a, outra para a pessoa que consente.

Attachment 2 Tables of values described throughout the dissertation project.

Table 9.1 Differences and correlations between the right and left eyes for all the measurements.

	RIGHT EYE (Mean±SD)	LEFT EYE (Mean±SD)	Difference±SD *p*	Correlation (r) *p*
SPHERICAL REFRACTION (D)	-0.38±0.81	-0.38±0.96	0.00±0.35 0.804*	0.839 **<0.001◊**
CYLINDRICAL REFRACTION (D)	-0.49±0.39	-0.43±0.26	-0.06±0.32 0.518*	0.714 **<0.001◊**
M (D)	-0.56±0.88	-0.56±0.99	0.00±0.33 0.931*	0.841 **<0.001◊**
J0 (D)	0.09±0.22	0.08±0.16	0.02±0.17 0.732*	0.567 **0.001◊**
J45 (D)	-0.05±0.11	0.01±0.15	-0.06±0.21 0.066*	-0.202 0.284◊
PUPIL SIZE IN MESOPIC CONDITIONS (mm)	5.60±0.70	5.66±0.68	-0.05±0.36 0.421+	0.869 **<0.001†**
Q_{steep}	-0.17±0.09	-0.16±0.10	-0.01±0.10 0.483+	0.489 **0.006†**
Axis of the Q_{steep} (degrees)	92±23	88±22	4±34 0.681*	-0.459 **0.011◊**
Q_{flat}	-0.41±0.14	-0.38±0.13	-0.02±0.10 0.217*	0.752 **<0.001◊**
Axis of the Q_{flat} (degrees)	74±77	64±75	10±116 0.504*	0.130 0.493◊
Sim K_{steep} (mm)	44.31±1.48	44.35±1.42	-0.04±0.37 0.518+	0.969 **<0.001†**
Axis of the SimK_{steep} (degrees)	93±16	90±20	3±27 0.853*	-0.457 **0.011◊**
Sim K_{flat} (mm)	43.33±1.34	66.33±77.12	-23.00±77.37 0.382*	-0.219 0.246◊
Axis of the SimK_{flat} (degrees)	63±76	43±1	20±76 0.629*	0.071 0.710◊
IS index (D)	-0.22±0.56	-0.21±0.55	0.00±0.43 0.990+	0.696 **<0.001†**
SRI	0.50±0.17	0.51±0.17	-0.01±0.16 0.782+	0.552 **0.002†**
SAI	0.63±0.22	0.64±0.24	-0.02±0.27 0.694*	0.490 **0.006◊**
WITHOUT CYCLOPLEGIA				
HCDVA (LogMAR)	-0.14±0.06	-0.15±0.08	0.01±0.05 0.238*	0.714 **<0.001◊**
LCDVA (LogMAR)	0.04±0.07	0.03±0.06	0.01±0.06 0.332*	0.516 **0.004◊**
LCDVA WITH +1.00D INDUCED DEFOCUS (LogMAR)	0.44±0.13	0.40±0.20	0.04±0.16 0.445+	0.639 **<0.001†**
LCDVA WITH -1.00D INDUCED DEFOCUS (LogMAR)	0.06±0.11	0.04±0.08	0.02±0.10 0.436*	0.590 **0.001◊**
RMS TOTAL HOA (µm)	0.279±0.143	0.274±0.152	0.005±0.079 0.371*	0.856 **<0.001◊**
RMS SPHERICAL ABERRATION (µm)	0.092±0.077	0.101±0.088	-0.010±0.031 0.072*	0.832 **<0.001◊**
RMS COMA ABERRATION (µm)	0.161±0.133	0.158±0.132	0.003±0.073 0.974*	0.739 **<0.001◊**
LDI (%)	2.75±1.71	2.68±1.72	0.07±0.70 0.666*	0.849 **<0.001◊**

BFCRad (mm)	13.00±3.97	12.84±3.98	0.16±1.71 0.619+	0.908 **<0.001†**
BFCIrreg (mm)	0.31±0.38	0.36±0.32	-0.05±0.50 0.424*	-0.089 0.640◊
BFCIrregSD (mm)	2.26±1.49	2.30±1.43	-0.04±1.69 0.957*	0.383 **0.037◊**
WITH CYCLOPLEGIA				
HCDVA (LogMAR)	-0.10±0.06	-0.10±0.06	0.00±0.06 0.922*	0.573◊ **0.003◊**
LCDVA (LogMAR)	0.16±0.08	0.15±0.08	0.01±0.06 0.411*	0.695 **<0.001◊**
RMS TOTAL HOA (μm)	0.193±0.058	0.198±0.066	-0.005±0.056 0.614+	0.605 **<0.001†**
RMS SPHERICAL ABERRATION (μm)	0.062±0.041	0.068±0.039	-0.006±0.026 0.206*	0.637 **<0.001◊**
RMS COMA ABERRATION (μm)	0.111±0.059	0.115±0.064	-0.004±0.061 0.715+	0.501 **0.005†**
LDI (%)	3.36±2.32	3.37±1.98	-0.01±1.12 0.674*	0.844 **<0.001◊**
BFCRad (mm)	14.25±4.63	14.41±4.14	-0.16±2.30 0.610*	0.831 **<0.001◊**
BFCIrreg (mm)	0.58±0.67	0.61±0.82	-0.03±0.77 0.943*	0.088 0.646◊
BFCIrregSD (mm)	2.82±1.60	2.89±1.59	-0.06±1.73 0.631*	0.398 **0.029◊**
WITH CYCLOPLEGIA AND AN INDUCED DEFOCUS OF +1.00D				
LCDVA AND +1.00D INDUCED DEFOCUS (LogMAR)	0.55±0.18	0.52±0.17	0.03±0.15 0.366+	0.623 **0.001†**
LDI (%)	4.74±4.15	5.17±4.50	-0.42±1.69 0.160*	0.937 **<0.001◊**
BFCRad (mm)	16.44±6.50	17.07±6.99	-0.63±2.57 0.161*	0.943 **<0.001◊**
BFCIrreg (mm)	0.80±0.90	0.97±1.08	-0.17±0.98 0.337*	0.430 **0.018◊**
BFCIrregSD (mm)	3.12±1.54	3.34±1.67	-0.22±1.75 0.215*	0.404 **0.027◊**
WITH CYCLOPLEGIA AND AN INDUCED DEFOCUS OF -1.00D				
LCDVA AND -1.00D INDUCED DEFOCUS	0.34±0.15	0.36±0.13	-0.02±0.14 0.545+	0.543 **0.005†**
LDI (%)	3.69±1.79	4.12±2.25	-0.43±1.40 0.051*	0.869 **<0.001◊**
BFCRad (mm)	15.25±3.61	16.02±4.17	-0.78±2.36 0.081+	0.826 **<0.001†**
BFCIrreg (mm)	0.55±0.51	0.54±0.63	0.00±0.64 0.846*	0.375 **0.041◊**
BFCIrregSD (mm)	2.66±1.65	2.87±1.77	-0.21±1.60 0.372*	0.529 **0.003◊**

Statistically significant differences are presented in **bold** and the underlined values refers to a strong correlation (r>0.800); (*) Wilcoxon Signed Ranks Test; (+) Paired Samples T-test; (◊) Spearman correlation; (†) Pearson correlation.

Table 9.2 Differences and correlations between the monocular and binocular light distortion parameters. Statistical significant differences and correlations are highlighted.

	MONOCULAR (Mean±SD)	BINOCULAR (Mean±SD)	Difference±SD *p*	Correlation (r) *p*
WITHOUT CYCLOPLEGIA				
LDI (%)	2.70±1.69	1.94±1.55	0.76±0.78 **<0.001***	0.736 **<0.001**◊
BFCRad (mm)	12.88±3.94	10.81±3.87	2.07±2.09 **<0.001***	0.738 **<0.001**◊
BFCIrreg (mm)	0.42±0.38	0.15±0.18	0.26±0.42 **0.004***	0.001 0.997◊
BFCIrregSD (mm)	2.30±1.30	1.50±1.53	0.80±2.14 0.059*	-0.204 0.280◊
WITH CYCLOPLEGIA				
LDI (%)	3.27±2.10	2.70±1.69	0.57±1.24 **0.009***	0.808 **<0.001**◊
BFCRad (mm)	14.18±4.19	12.83±3.99	1.35±2.44 **0.011***	0.788 **<0.001**◊
BFCIrreg (mm)	0.58±0.56	0.48±0.37	0.10±0.62 0.554*	0.273 0.145◊
BFCIrregSD (mm)	2.88±1.52	2.90±0.87	-0.02±1.77 0.699*	0.050 0.792◊
WITH CYCLOPLEGIA AND AN INDUCED DEFOCUS OF +1,00D				
LDI (%)	5.07±4.40	3.53±2.83	1.54±2.13 **<0.001***	0.839 **<0.001**◊
BFCRad (mm)	16.93±6.87	14.53±5.36	2.40±2.69 **<0.001***	0.919 **<0.001**◊
BFCIrreg (mm)	0.95±1.07	0.61±0.56	0.34±1.04 0.115*	0.265 0.156◊
BFCIrregSD (mm)	3.19±1.69	2.91±1.22	0.28±1.73 0.409*	0.191 0.311◊
WITH CYCLOPLEGIA AND AN INDUCED DEFOCUS OF -1,00D				
LDI (%)	3.91±2.32	3.15±1.44	0.77±1.33 **0.001***	0.881 **<0.001**◊
BFCRad (mm)	15.56±4.29	14.11±3.24	1.45±2.17 **0.001***	0.877 **<0.001**◊
BFCIrreg (mm)	0.55±0.63	0.58±0.61	-0.04±0.77 0.428*	0.087 0.649◊
BFCIrregSD (mm)	2.63±1.83	2.64±1.51	-0.01±2.08 0.926*	0.324 0.081◊

Statistically significant differences and correlations are presented in **bold** and the underlined values refers to a moderately strong and strong correlation (r>0,500 and r>0,800 respectively); (*) Wilcoxon Signed Ranks Test; (◊) Spearman correlation.

Table 9.3 Differences between light distortion parameters without and with cycloplegia in monocular and binocular conditions, with the best distance correction. Statistical significant differences and correlations are highlighted.

	WITHOUT CYCLOPLEGIA (Mean±SD)	WITH CYCLOPLEGIA (Mean±SD)	Difference±SD *p*	Correlation (r) *p*
MONOCULAR CONDITIONS				
LDI (%)	2.70±1.69	3.27±2.10	-0.57±1.28 **0.014***	0.793 **<0.001◊**
BFCRad (mm)	12.88±3.94	14.18±4.19	-1.30±2.86 **0.019**+	0.753 **<0.001†**
BFCIrreg (mm)	0.42±0.38	0.58±0.56	-0.16±0.72 0.289*	-0.116 0.541◊
BFCIrregSD (mm)	2.30±1.30	2.88±1.52	-0.57±2.00 0.141*	-0.006 0.973◊
BINOCULAR CONDITIONS				
LDI (%)	1.94±1.55	2.70±1.69	-0.76±1.42 **0.001***	0.618 **<0.001◊**
BFCRad (mm)	10.81±3.87	12.83±3.99	-2.01±3.36 **0.001***	0.635 **<0.001◊**
BFCIrreg (mm)	0.15±0.18	0.48±0.37	-0.32±0.42 **0.001***	-0.074 0.696◊
BFCIrregSD (mm)	1.50±1.53	2.90±0.87	-1.40±1.61 **<0.001***	0.191 0.312◊

Statistically significant differences and correlations are presented in **bold** and the underlined values refers to a moderately strong correlation (r>0,500); (*) Wilcoxon Signed Ranks Test; (+) Paired Samples T-test; (◊) Spearman correlation; (†) Pearson correlation.

Table 9.4 Differences and correlations between light distortion parameters in monocular and binocular conditions between the different levels of induced spherical defocus, always with the best distance correction. Difference values refer to “second condition – first condition”. Statistical significant differences and correlations are highlighted.

LEVELS OF DEFOCUS COMPARED	0.00D vs. +1.00D		0.00D vs. -1.00D		+1.00D vs. -1.00D	
	Difference±SD *p*	Correlation (r) *p*	Difference±SD *p*	Correlation (r) *p*	Difference±SD *p*	Correlation (r) *p*
MONOCULAR CONDITIONS						
LDI (%)	1.80±3.68 **0.002***	0.752 **<0.001**◊	0.64±2.44 **0.049***	0.560 **0.001**◊	-1.16±4.00 0.279*	0.512 **0.004**◊
BFCRad (mm)	2.75±5.06 **0.003***	0.760 **<0.001**◊	1.38±4.26 **0.038***	0.582 **0.001**◊	-1.37±6.13 0.344*	0.543 **0.002**◊
BFCIrreg (mm)	0.37±1.16 0.120*	-0.099 0.604◊	-0.03±0.78 0.804*	0.096 0.615◊	-0.40±1.27 0.094*	0.019 0.920◊
BFCIrregSD (mm)	0.31±2.45 0.845*	-0.138 0.466◊	-0.24±2.48 0.405*	-0.064 0.736◊	-0.55±2.09 0.154*	0.307 0.099◊
BINOCULAR CONDITIONS						
LDI (%)	0.83±2.20 **0.020***	0.637 **<0.001**◊	0.44±1.42 0.056*	0.551 **0.002**◊	-0.39±2.42 0.732*	0.476 **0.008**◊
BFCRad (mm)	1.71±3.85 **0.020***	0.681 **<0.001**◊	1.28±3.34 **0.038***	0.562 **0.001**◊	-0.43±4.58 0.613*	0.527 **0.003**◊
BFCIrreg (mm)	0.13±0.65 0.304*	0.106 0.576◊	0.11±0.60 0.622*	0.337 0.068◊	-0.02±0.87 0.674*	-0.080 0.676◊
BFCIrregSD (mm)	0.01±1.37 0.697*	0.100 0.600◊	-0.25±1.62 0.489*	0.183 0.332◊	-0.26±1.65 0.632*	0.244 0.193◊

Statistically significant differences and correlations are presented in **bold** and the underlined values refers to a moderately strong correlation (r>0,500); (*) Wilcoxon Signed Ranks Test; (◊) Spearman correlation.

Table 9.5 Correlations between light distortion parameters in monocular conditions with the three types of high order aberrations evaluated (Total, Spherical and Coma HOA). Statistical significant correlations are highlighted.

	TOTAL HOA	SPHERICAL HOA	COMA HOA
		Correlation (r) *p*	
WITHOUT CYCLOPLEGIA (MESOPIC NATURAL PUPIL: 5.64±0.65MM)			
LDI (%)	0.173 0.360◊	0.463 **0.010**◊	-0.034 0.859◊
BFCRad (mm)	0.168 0.376◊	0.459 **0.011**◊	-0.040 0.832◊
BFCIrreg (mm)	-0.100 0.599◊	-0.049 0.796◊	-0.028 0.882◊
BFCIrregSD (mm)	-0.193 0.307◊	-0.141 0.458◊	-0.200 0.290◊
WITH CYCLOPLEGIA (5MM LIMITED PUPIL)			
LDI (%)	-0.001 0.997◊	0.134 0.480◊	0.002 0.993◊
BFCRad (mm)	-0.039 0.837†	0.230 0.221†	-0.036 0.848†
BFCIrreg (mm)	0.012 0.950◊	0.358 0.052◊	-0.180 0.342◊
BFCIrregSD (mm)	0.376 **0.040**◊	-0.004 0.983◊	0.372 **0.043**◊
WITH CYCLOPLEGIA AND AN INDUCED DEFOCUS OF +1.00D (5MM LIMITED PUPIL)			
LDI (%)	0.044 0.818◊	0.279 0.135◊	-0.041 0.832◊
BFCRad (mm)	0.043 0.820◊	0.268 0.153◊	-0.047 0.807◊
BFCIrreg (mm)	0.243 0.195◊	0.147 0.438◊	0.187 0.321◊
BFCIrregSD (mm)	0.001 0.994◊	0.092 0.628◊	0.028 0.885◊
WITH CYCLOPLEGIA AND AN INDUCED DEFOCUS OF -1.00D (5MM LIMITED PUPIL)			
LDI (%)	-0.150 0.430◊	-0.104 0.583◊	-0.141 0.458◊
BFCRad (mm)	-0.148 0.434◊	-0.098 0.606◊	-0.138 0.466◊
BFCIrreg (mm)	0.248 0.187◊	-0.143 0.452◊	0.274 0.143◊
BFCIrregSD (mm)	0.061 0.750◊	<0.001 0.999◊	0.054 0.776◊

Statistically significant correlations are presented in **bold** and the underlined values refers to a fairly correlation (r>0,300); (◊) Spearman correlation.

Table 9.6 Correlations between topographic parameters of corneal quality and light distortion measures at different conditions of measurement of the light distortion. The highlighted values respect the significant correlations found.

	Q Correlation (r) *p*	SRI Correlation (r) *p*	SAI Correlation (r) *p*
WITHOUT CYCLOPLEGIA			
LDI (%)	0.204 0.279†	0.224 0.233†	0.159 0.400†
BFCRad (mm)	0.073 0.700◊	<u>0.519</u> **0.003**◊	<u>0.502</u> **0.005**◊
BFCIrreg (mm)	0.036 0.851◊	0.242 0.198◊	<u>0.371</u> **0.044**◊
BFCIrregSD (mm)	0.132 0.488◊	0.308 0.098◊	0.178 0.347◊

Statistically significant correlations are presented in **bold** and the <u>underlined</u> values refers to fairly (r>0.300) and moderately strong (r>0.500) correlations; (◊) Spearman correlation; (†) Pearson correlation.

Table 9.7 Correlations between the variation on monocular LCDVA with a positive and negative defocus and the variation on monocular light distortion parameters in cycloplegic condition with positive and negative defocus. No statistically correlations were found.

Variation on LCDVA with cycloplegia and induced defocus of +1.00D Correlation (r) *p*	
LDI (%)	0.292 0.450◊
BFCRad (mm)	0.262 0.372◊
BFCIrreg (mm)	-0.157 0.682◊
BFCIrregSD (mm)	0.079 0.797◊
Variation on LCDVA with cycloplegia and induced defocus of -1.00D Correlation (r) *p*	
LDI (%)	0.033 0.830◊
BFCRad (mm)	-0.054 0.799†
BFCIrreg (mm)	0.081 0.887◊
BFCIrregSD (mm)	-0.024 0.911†

(◊) Spearman correlation; (†) Pearson correlation.