Optics of human eye: 400 years of exploration from Galileo's time

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We present a brief historical background and a description of the main features of the eye's optical properties: the eye is a simple, but rather optimized, optical instrument. It is only since Galileo's time that the importance of the eye as a part of different optical instruments has driven a continuous scientific exploration of ocular optics. In the past decade, the use of wavefront sensing technology allowed us to complete our understating of eye optics as a robust aplanatic system. © 2010 Optical Society of America

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1. Introduction

The human eye is a paradigmatic example of a relatively simple optical instrument providing exceptional functionality. But even with the simplicity of ocular optics, there was a long process in reaching the nearly complete understanding we have today. The optics of the eye resemble an aplanatic design [1] with a partial correction of both spherical aberration and coma. This is due to a natural balance between the aberrations of the cornea and the lens in the young eye [2], which is progressively lost during normal aging [3]. Although interest in the eye is intrinsic to human nature, it was around Galileo's time when scientific exploration of the eye began. From then, it continuously advanced, in part due to the great evolution of artificial optical instruments, paradoxically developed to actually bypass the eye's limitations of resolution.

At the time of Galileo's first use of the telescope for astronomical observations, there was already a basic understanding of some of the refractive errors of the human eye [4,5]. It was evident that a normal emmetropic eye was most comfortable viewing light originating from a far distance. This observation was one of the reasons why the Galilean telescope worked adequately when a secondary negative lens (Galilean eyepiece) was placed in combination with a large focal length positive lens (objective lens).

In the years to come, three factors were identified to limit the optical performance of the Galilean telescope [6–8]: a limited field of view—intrinsic to a telescope with a negative eyepiece–and chromatic and spherical aberrations (also, some historical studies suggest that coma might have been an issue for Galileo's observations). Concerning these three defects, only the field of view in the eye is superior to the Galilean telescope. However, the human eye is affected by chromatic and spherical aberrations, coma, and other higher order aberrations.

In the case of the telescope, the impact of Galileo's discoveries generated a "telescope race," quickly improving the optical quality of the instrument: increasing the field of view with Kepler's eyepiece design, suppressing chromatic effects with Newton's reflective designs, and minimizing aberrations with the adequate surface shape calculated after Snell's law. But in the case of the human eye, understanding and correction of ocular aberrations followed a slower evolution. Previous to Galileo's time, spectacles for the correction of presbyopia and myopia were already used and sold by Italian glassmakers in Florence [4,5] based on empirical testing, until Kepler

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correctly described how spherical lenses compensate myopic and hyperopic refractive errors. However, it took a long time to characterize and correct astigmatism. At the beginning of the nineteenth century, Thomas Young correctly described the astigmatism of his left eye [9], and it took almost 30 years to find the appropriate astigmatic correction. It was Airy, in 1827, who suggested the use of cylindrical-shaped surfaces to compensate for refractive errors along certain meridians, a spectacle design that is still very common today [5].

The ocular spherical and chromatic aberrations were both well known, due to the limitation they imposed on telescopes and microscopes. The first observation of spherical aberration in the human eye seems to be made by Thomas Young in his famous 1801 publication "On the mechanism of the eye" [9,10] and later by Helmholtz in his *Treatise on Physiological Optics* in 1855. The chromatic effects in the eye were initially mentioned by Newton [11] and later by Young [12]. However, the correction of chromatic aberration by using achromatizing lenses was only tried in the middle of the twentieth century [13], and some variations of corrector providing wide-angle performance were proposed even recently [14].

In this article, we provide a brief historical perspective of how we gained knowledge of the optical components of the eye, the cornea, and the crystalline lens, describing the on-axis monochromatic aberrations of each component, and the step-by-step procedure of building more and more accurate optical models of the eye, until the current understanding of the eye's optics.

2. Brief History of Main Advances on Optics of the Eye

In the eye, only two lenses are used to focus light from a distance source on the retina. If compared to an artificial optical system designed for the same purpose (for instance, a teleobjective lens), this number may appear as too small (see a schematic representation in Fig. 1). The number of elements mounted in the artificial optical system is due to a more or less demanding correction of aberrations. Whether this type of optimization strategy was also presented in the human eye could not be elucidated until a characterization of each separate component was given, and that took 400 years from Galileo's time.

In a simplified historical revision [15], Galileo's contemporaries, Kepler, Scheiner, and Descartes, contributed to the initial understanding of the eye as an optical instrument, realizing that the image on the retina was inverted and providing the first description of the optical components. Later, Huygens built a physical eye model made of two hemispheres filled with water and a diaphragm. But, it was only at the beginning of the nineteenth century when Thomas Young produced the first geometric optics description of the cornea and the lens. The radii of curvature of corneal and lens surfaces, as well as the anterior chamber depth and the refractive index values, were strikingly well estimated for those times. Later, Moser (1844) and Listing (1851) built schematic eyes using spherical surfaces to describe the cornea and lens. The Listing eye model was improved by Helmholtz modifying the positions of the lens surfaces. Those schematic eyes were three surface models, one for the cornea and two for the crystalline lens. The radius of curvature of the posterior corneal surface was measured for the first time by Tscherning, and he described the first four-surface schematic eye model in 1900. After that, based on the improvement of the techniques for measuring the eye curvatures and axial distances, several eye models were proposed in the past century, and some of them became very popular, such as the Gullstrand model discussed in Ref. [16], the Le Grand [17] and the Emsley [18] eye models. The use of these spherical models should be restricted to the paraxial geometric optics. They were used to estimate the cardinal planes and points of the eye, to design new spectacles and, after the first modern cataract surgery {in 1949 an intraocular lens (IOL) was implanted in an eye for the first time [19]}, to calculate the power of the IOL.

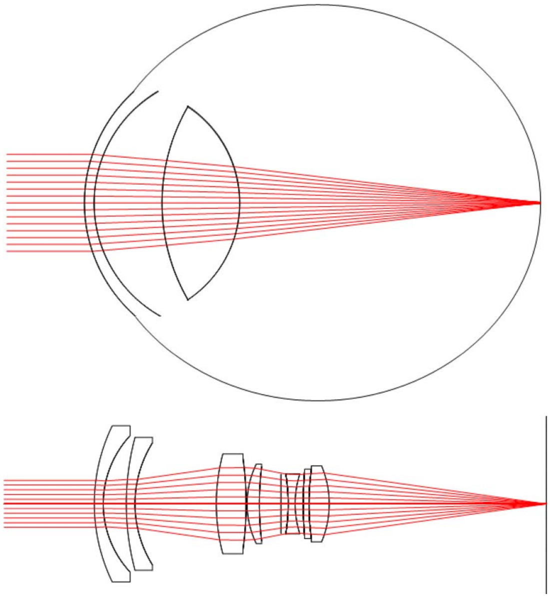

Fig. 1. (Color online) Schematic example of a human eye model compared with an artificial optical objective.

However, these simple models could not be used to fully understand the aberrations of each component. Because the surfaces used were rotationally symmetrical spheres, ray tracing through the schematic eyes would immediately show that the predicted values did not agree with the measurements. The accuracy of the models was restricted to the paraxial optics. After nearly 350 years, the actual aberrations of the cornea and the lens were largely unknown.

The first attempt to localize where astigmatism originates in the eye was performed by Young in 1801 [9]. His scientific curiosity led him to question if his own astigmatism was originated either by the cornea or by the crystalline lens. He noticed that when immersed in water (with a similar refractive index as the cornea), he would cancel the corneal contribution, and since the astigmatism persisted, he assumed it was induced by the crystalline lens.

The sources of aberrations in the eye were not studied until the decade of 1970 (previously, in 1961 Smirnov had measured the wave aberration of the human eye for the first time [20] with a vernier-type subjective method). At this time, the first versions of corneal topographers (based on the deformations observed in the reflected image of a series of concentric rings at the cornea) began to be used as ophthalmic tools. This permitted the reconstruction of the first corneal surface shape, and therefore the calculation of corneal (first surface) aberrations. In 1973, El Hage and Berny [21], using one of these instruments, estimated the spherical aberration of the cornea, obtaining positive values, i.e., the peripheral rays cross the optical axis in front of the paraxial rays. Because there was no direct access to the crystalline lens *in vivo*, they measured spherical aberration of the total eye using a Foucault test (also a well-known technique from telescope optics). When they compared both sets of data, they realized that the spherical aberration of the cornea was much higher than the spherical aberration of the complete eye. They inferred that the spherical aberration of the crystalline lens should have negative values, providing a balance of the positive spherical aberration of the cornea. An experiment performed later by Millodot and Sivak [22], using goggles filled with water to cancel the corneal contribution (similar to what Young did over 200 years before), obtained more variability in the sign of the lens spherical aberration. In 1993, Tomlinson *et al.* [23] confirmed the results from El Hage and Berny [21] using a mixed objective/psychophysic technique.

Some of the advances in the instruments to assess objectively the optical quality of the eye allowed us to revisit this issue in the 1990s. By using the double-pass technique [24,25], we suggested [26] that not only the spherical aberration, but also other higher order aberrations, could be balanced between the cornea and the lens. The introduction of the Hartmann–Shack wavefront sensor to measure the aberrations of the eye [27,28] permitted the design of additional experiments, including revisiting the measurements of the aberrations of the eye immersed in water [29,30].

In addition, the use of improved Hartmann–Shack wavefront sensors allowed us to perform real-time analysis of the aberrations [31] and to build adaptive optics systems for the human eye [32–34].

The advances on the understanding of the optical components led to a higher degree of complexity in the elaboration of the schematic eye models. Trying to improve the prediction of the spherical aberration measurements, several authors incorporated conic surfaces to describe the cornea and the lens [35–37]. The corneal asphericity values were taken from corneal topography measurements, but the lens surface asphericity values were somehow difficult to measure, and, in many cases, they were used as variables to adjust the model to certain values or they were measured from *ex vivo* lenses. Today, the exact values of asphericity of the lens surfaces are still a matter of discussion, with only available data from optically corrected Scheimpflug images [38] that show large standard deviation errors in repeatability. Additional advances in the schematic eyes added a refractive gradient index to the lens [39–41]. However, the measurements of this parameter are also difficult and scarce. It is usually incorporated into the optical models via optimization to fit a more easily measurable variable, such as the peripheral refractive errors. The new models also benefited from advances in the understanding of the chromatic properties of the eye, either the longitudinal chromatic aberration or the lateral chromatic aberration [42–44]. Another aspect traditionally modeled is accommodation, from the purely paraxial models (see, for instance, the Bennett and Rabbets eye model [45] that consider only changes in lens curvature) to more sophisticated eye models that include the changes in thickness, asphericity, and refractive index as a function of accommodation [37,46].

In general, the latest schematic eye models provide results that are close to an average population. However, due to the individual variability in the aberrations, they might not be individually accurate. New customized eye models incorporating individual data will be discussed in the next section.

3. Current Understanding of Eye Optics: Aplanatic Design

The magnitude of the eye's higher order aberrations (beyond defocus and astigmatism) only represents approximately around 10% of the total aberrations of the normal eye [47]. Although a large variability between subjects is typically presented, the effect of these aberrations is crucial to degrade the retinal image quality of the human eye. In terms of statistics in a relatively large population [47–49], only spherical aberration has a slightly positive mean value different from zero. However, of interest is not only the global magnitude of aberrations in the eye, but also the contribution to those aberrations of the ocular components.

In this respect, two aberration terms show a significant level of compensation between cornea and lens: spherical aberration and horizontal coma. In these two cases, the cornea has higher values than the complete eye. To understand the underlying mechanism for this compensation, we must know more about the sources of these aberrations. The crystalline lens may induce negative spherical aberration mainly due to three factors: curvature, asphericity, and gradient index. Simulations with a lens model with only spherical surfaces show that curvature alone cannot be responsible for inducing negative spherical aberration. Therefore, the lens contribution must be determined by asphericity or gradient index. To what extent the lens contribution is from either one or another factor, or a combination of both, is not experimentally determined yet.

The improvement of the *in vivo* imaging techniques of the anterior chamber depth might allow us to acquire more precise data of the lens surface profiles that, in combination with other optical parameters, could be used to infer the gradient index and its actual contribution to the negative spherical aberration. The understanding of the compensation of coma required more experiments. It was initially hypothesized that a particular location of the lens, with respect to the cornea or the gradient refractive index of the lens, might induce this effect [29]. However, new experiments indicated that the angular misalignment between the line of sight (the line connecting the center of the entrance pupil and the fixation stimulus) and the pupillary axis (the line perpendicular to the cornea passing through the center of the entrance pupil) was linearly related to the generation of coma in both the cornea and the lens [30,50]. This angular misalignment is called the angle kappa, or lambda, of the eye, and the average magnitude in normal eyes is around 5° [17]. Those eyes with a small angle kappa showed nearly no coma compensation, while those with a large angle kappa had large values of both corneal and lenticular coma, but with opposite signs.

By using a method based on the recording of Purkinje images, it was possible to measure the angle kappa together with the lens tilt and decentration [51]. Figure 2 presents some alignment results in a group of normal young eyes from a recent experiment [2]. The left panel shows the decentration of the lens with respect to the center of the pupil. The values are small—around zero (not larger than 0.3 mm). The values of angle kappa are shown on the right panel. The horizontal component clearly dominated over the vertical component and the magnitudes were around 5°. Individually ray tracing customized eye models that introduce the complete actual cornea topography and a crystalline lens with the corresponding adjusted values of spherical aberration for each subject showed that the real values of lens decentration had a very small effect in the compensation of coma. However, neglecting the values of angle kappa in any of the personalized eye models had very significant impact on the values of coma. This suggested that coma was "somehow" closely related to the values of angle kappa.

The origin of angle kappa comes from the systematic noncoincidence of the position of the fovea and the point where the optical axis intercepts the retina. Angle kappa is smaller in myopes (longer eyes) than in hyperopes (shorter eyes) [17]. This is easy to understand based on a simple model in which the differences in those eyes are the axial length, with a relatively similar foveal location. Figure 3 shows an example of the structure of aberrations in a group of eyes with different refractive errors. Three small groups of subjects (hyperopic, emmetropic, and myopic) were sorted by their refractive error. Total ocular aberrations, corneal aberrations, angle kappa, and lens decentration were measured. The internal lens aberrations were calculated, subtracting corneal to total aberrations [29]. All aberration values were obtained for a 5 mm pupil diameter. Figure 3(a) shows the spherical aberration plotted against refraction. The spherical aberration for the cornea was clearly

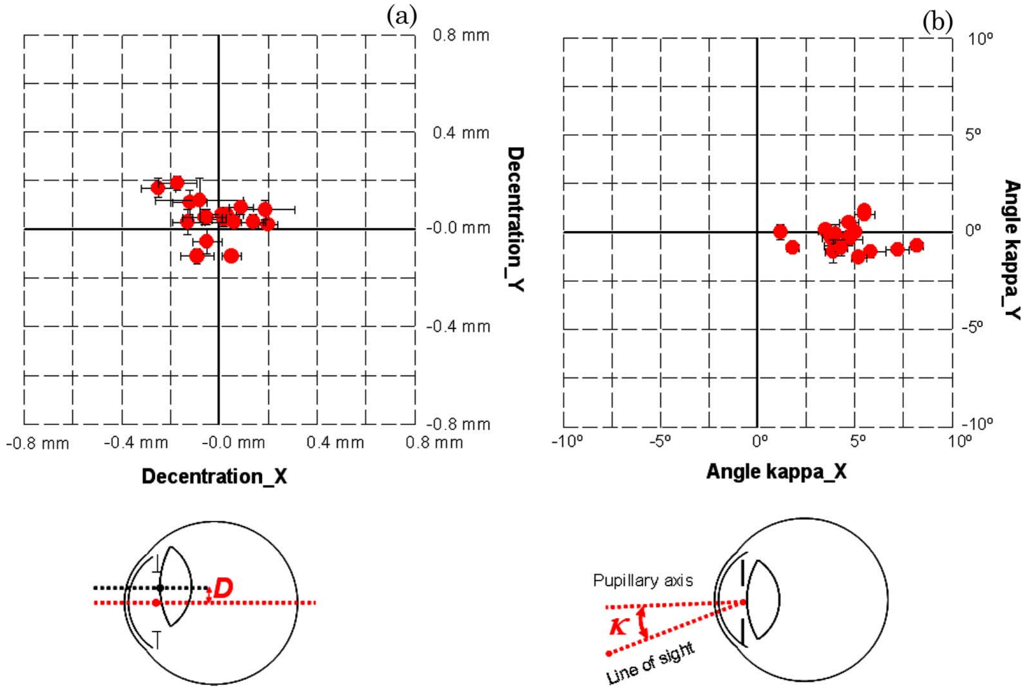

Fig. 2. (Color online) (a) Values of lens decentration and (b) angle kappa in a group of normal subjects.

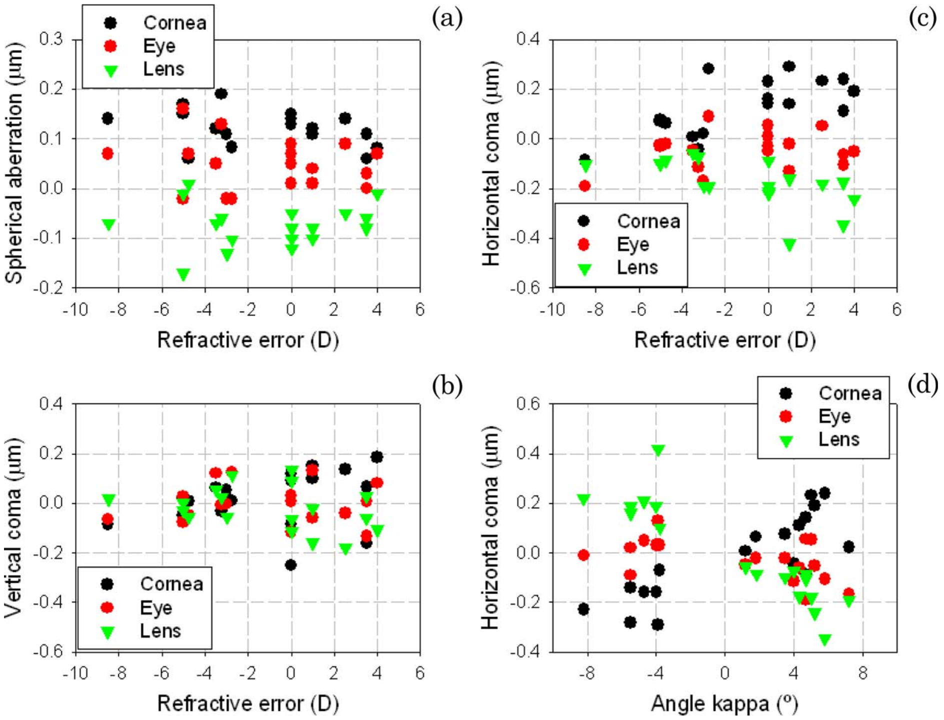

Fig. 3. (Color online) (a) Spherical aberration, (b) vertical coma, and (c) horizontal coma as a function of the refractive error in a group of normal young subjects. (d) Horizontal component of coma as a function of angle kappa. Circles represent the values for the cornea (measured from corneal topography) and the corresponding values for the total eye (measured using a Hartmann–Shack wavefront sensor). The internal aberrations (triangles) were obtained as the direct subtraction of corneal values to total values.

positive, as opposed to the negative values of the lens. The compensation was not affected by the refractive error, which is also a consequence of the axial nature of the refractive errors (i.e., the myopic eyes are longer and hyperopic eyes are shorter than the normal eye). Concerning coma, compensation is observed in the horizontal direction [Fig. 3(b)] but mainly for the hyperopic eyes (those with larger angle kappa). Along the vertical direction, Fig. 3(c) data are scattered and the compensation effect was not statistically significant. The compensation of horizontal coma was related to the angle kappa of the eye [Fig. 3(d)]. The larger the angle, the larger will be the corneal and lenticular coma, but both with opposite signs. The next step in the understanding of the compensation of the aberrations compensation mechanism was to realize that the opposite signs in coma for the cornea and the lens originated from the different shape factors of each component [1,2]. A simplified model using Seidel aberration theory for lenses immersed in nonsymmetrical refractive index mediums [52] shows that coma depends on the shape of the components, the linear angular dependence, the position of the object plane, and the refractive indices. These results were corroborated with exact ray tracing calculations.

An example of this situation is shown in Fig. 4: the three eye models have the same cornea and the same optical power for the crystalline lens. However, the shapes of the lenses are different. The upper case is the realistic lens with the actual shape, but the other two cases, while the lenses keep the same power, have opposite values of shape factors that are not physiologically realistic. For each model, the incoming light subtends 5° with respect to the optical axis, simulating an average 5° angle kappa. On the right column, the point-spread functions (without

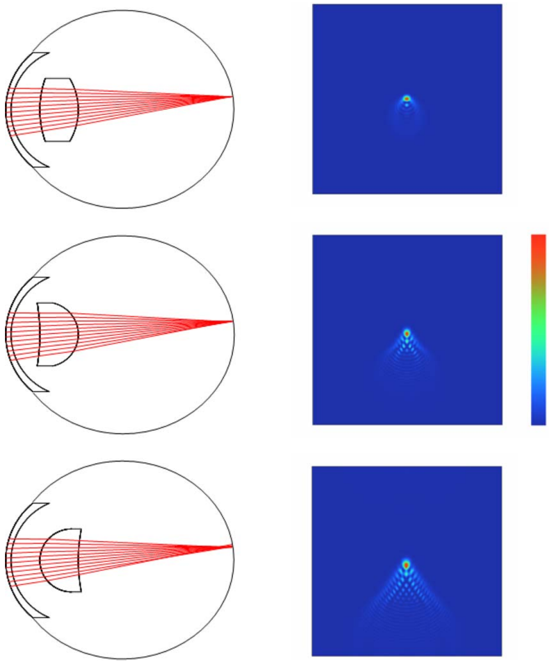

Fig. 4. (Color online) Examples of eye models and their associated point-spread functions; see text for additional details.

the rotationally symmetrical terms) of each case are shown. The situation yielding the lower amount of coma corresponds precisely to the physiologically accurate model, while the rest of the lens shapes, although optically possible, produce higher values of off-axis coma.

These results support the idea that the eye's optics is an aplanatic design, a configuration where spherical aberration and coma are approximately corrected. Because the compensation is not perfect, as can exist in an artificial system, the eye is still affected by aberrations.

4. From Eye's Design to Ophthalmic Corrections: Current and Future Advances

The fact described in the previous section, that corneal and crystalline lens aberrations are partially balanced, has generated research on the hypothetical situations in which this fine tuning might be disrupted. Certainly, some modification of either the cornea or the lens can occur in ophthalmic surgery situations, such as refractive or cataract surgery. Standard refractive surgery procedures can disrupt the aberration compensation, especially in hyperopic corrections [53], leading to the idea that improved ablation profiles, inducing less aberration, may be required. Cataracts are opacifications of the crystalline lens that typically occur with age. The common current solution is to replace the opaque lens by an artificial IOL. The first experimental works on the *in vivo* optical quality of eyes implanted with IOLs showed an apparent paradox [54,55]. The retinal image quality appeared to be similar to that of normal patients of the same age. IOLs are manufactured with high optical quality standards [56], better than isolated older human lenses. However, when implanted into the eye, the resulting optical quality was not significantly improved. The compensation of aberrations in the normal eye provided an explanation to this paradox and, more interestingly, a potential solution. The best IOL is not diffraction limited, but a lens with opposite aberrations to that of the cornea, mimicking the situation in the young crystalline lens. This actually opened a new era for the optical design of IOLs. Some designs with aspherical optics had been proposed before [57], but it was within the context of the compensation of aberration [58], with a better understanding of the optics of the eye, when this technology was ready to enter the field of ophthalmology [59]. Along these lines, more recently we proposed another design of IOL to correct also the coma generated by the typical kappa angles in the eye [60]. The idea for this design was to maintain the appropriate shape factors of the IOL to compensate corneal coma for each refractive power model. This model also incorporated an aspheric surface to compensate for corneal spherical aberration.

The current, better understanding of the eye's optics reviewed in this paper will surely contribute to new potential practical applications. Virtually every future idea for visual correction will need to consider carefully the optical properties of the eye. Combining new materials and surgical technologies with optics has the potential for improvements in every approach. Adaptive optics applications [32,33] for visual simulation and testing [61,62] and high-resolution retinal imaging [63,64], still mostly restricted to the research laboratories, may soon become routine clinical procedures. Completing the understanding of the optical properties of the lens, and the changes related to aging and accommodation, are still challenging open topics. Of course this revision does not cover all the issues on eye optics, since we are restricted to monochromatic and on-axis foveal situations. However, peripheral aberrations [65], with possible potential in relation with experiments of myopia progression and control, and chromatic aberrations are other interesting aspects still subject of extensive research.

In the study of the human eye, there is a convergence of optical physics and photonics together with materials, instrumentation, and surgery. Ideally, a combination of all these disciplines will make it possible to provide patients with a better assessment, evaluation, and correction in the future. The giants of the field, from Galileo to Young or Helmholtz, would surely be amazed to see the current understanding of most of the main problems.

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