MEASURING AND MODELING THE EFFECTS OF OCULAR ABERRATIONS ON VISUAL ACUITY

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Abstract

The recent development of novel optical techniques has made it possible to control the ocular aberrations with high precision and investigate the limits of visual performance. Using these techniques, we developed a vision simulator to measure visual acuity in extreme conditions of high-resolution ophthalmic correction, and to study the effects of the optical blur on visual perception. Fast and accurate psychophysical methods were used to obtain reliable results on small changes of visual performance. We also used a customised model of visual acuity to predict and understand the relation between the retinal image quality and the visual perception. This work provides novel insight into the optical and neural limitations of visual performance.

Vision consists of different stages: an image is first formed on the retina by the optical system of the eye; then this image is sampled by the photoreceptors, and processed at the retinal and cortical levels. The optical quality of the image seen by a subject is degraded by optical aberrations. The main defects, myopia, hyperopia, astigmatism, can be corrected by conventional ophthalmic solutions (spectacles, contact lenses…). However, other imperfections of the eye, called higher-order aberrations (HOA), create small, yet significant, distortions of the image. In the last fifteen years, novel optical techniques, namely adaptive optics (AO) techniques, have been adapted from astronomy to vision science to gain a better control and monitoring of these imperfections (Liang et al., 1997). With such techniques, it is possible to obtain a better optical quality and thus investigate visual performance limits. The aim of this work is to use psychophysical and numerical simulation techniques to explore the effects of a fine optical correction of the eye on visual performance, and investigate the optical and neural fundamental limits of vision.

We will first present some experimental data on the effects of HOA on visual performance, once the main defects have been corrected with spectacles. While HOA have some distorting effects on the retinal image, it is not clear how they affect visual performance. The emphasis was put on measuring functional vision in a range of natural lighting conditions. Light level affects both the optical quality – as the light is decreased the pupil dilates and more image distortions appear, as well as the retinal processing – as the light is decreased the signal-to-noise ratio is decreased and more spatial summation occurs. Therefore it is important to take into account this parameter to evaluate the benefit of such a fine optical correction for everyday vision.

We will also show how an early process vision model can be customized to predict visual performance of changes in visual performance for specific tasks and optical conditions. We will present some work on the validation of such models.

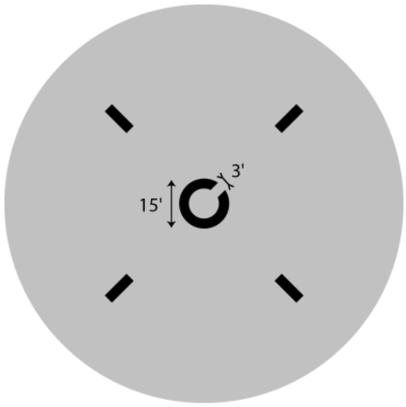

Fig. 1. Stimulus used for the functional visual test.

Measuring the effects of ocular aberrations on visual performance

We built a so-called “AO vision simulator” which allows the measurement and manipulation of the optical aberrations of the human eye while performing visual tests (Dalimier et al., 2005). We used the instrument to measure the benefit in visual performance gained after correction of HOA versus a conventional ophthalmic correction.

Experimental method

Five subjects were recruited, aged 22±3 years old. They had no more than 1D refractive prescription and no history of ocular disease. The research was approved by the National University of Ireland, Galway, Ethics Committee and followed the tenets of the Declaration of Helsinki. Visual performance was assessed using the Contrast Acuity Test (CAT) developed by Chisholm et al. (2003). This test, at the crossroad of the conventional visual acuity test and contrast sensitivity test, is more representative of functional vision. It consists in measuring the contrast threshold necessary to resolve the orientation of a Landolt C subtending 15 minutes of arc (see Figure 1). A four-alternative, forced-choice discrimination task was designed: the subject had to choose between four positions of the gap as indicated by the guide bars on Figure 1. Contrast threshold was assessed using an adaptive psychophysical method, the QUEST procedure developed by Watson and Pelli (1983). The stimulus was displayed in green on a CRT monitor or a DLP projector and viewed through the optical system. The subject was stabilized with the help of a bite bar, and his pupil was dilated with Tropicamide 1%. An artificial pupil was used to delimit the light beam entering the eye, thereby mimicking the natural pupil of the eye.

The visual tests were performed repetitively in different conditions. The pupil size was set to 6mm diameter for all subjects and additionally to 5, 4, and 3 mm diameter for some subjects. The light level was adjusted independently using neutral density filters: the retinal illuminance values varied from 1000 Td (photopic range) to 0.5 Td (low mesopic range). For each set of conditions (pupil size, light level), CAT measurements were carried out with the eye having a conventional ophthalmic correction of his aberrations such as that given by spectacles or contact lenses, then with the finer correction of all aberrations including HOA. The ratio of the contrast sensitivity (inverse of contrast threshold) measured with HOA correction to that measured without HOA correction was used to define the visual benefit. The visual benefit was measured five times and averaged for each subject and each set of conditions.

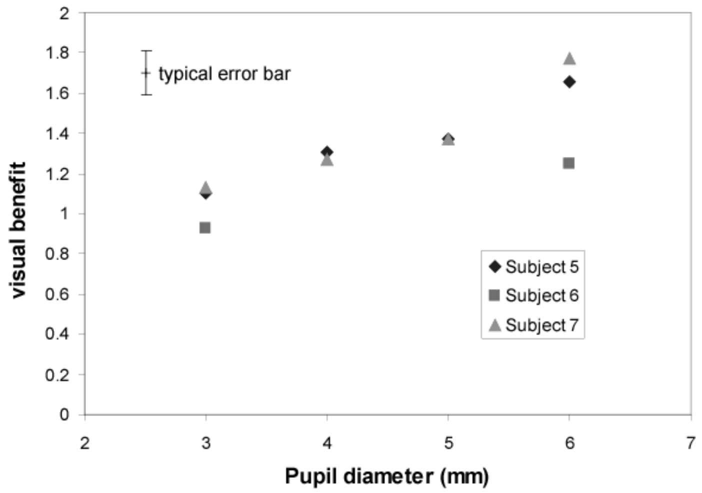

Fig.2 Effect of pupil size on visual benefit for functional vision in the photopic range.

Experimental results

The results of this experiment are shown in Figures 2, 3 and 4. Figure 2 illustrates the visual benefit gained with the correction of HOA as a function of pupil size at high light level (E_r = 1000 Td). It shows that as expected, when the pupil size is decreased, the amount of HOA decreases and the visual benefit gained with their correction decreases. For a 3mm diameter pupil, the benefit is close to 1, which means that the eye has naturally sufficient optical quality at that size. Figure 3 shows, for a constant pupil size (6 mm diameter), the visual benefit as a function of light level. It is interesting to see that as the light level is decreased, the visual benefit is decreased. This indicates that at low light level, the drop in neural contrast sensitivity moderates the optical blur. To appreciate the importance of HOA for everyday vision, we fitted the data obtained to the diameter the pupil naturally dilates to in ambient light (de Groot and Gebhard, 1952). The curve obtained illustrates the expected visual benefit in real life with the best retinal image produced (see Figure 4). It indicates that for all light levels, the benefit remains limited due to the combined action of the pupil constriction at high light level, and the drop in neural contrast sensitivity at low light level.

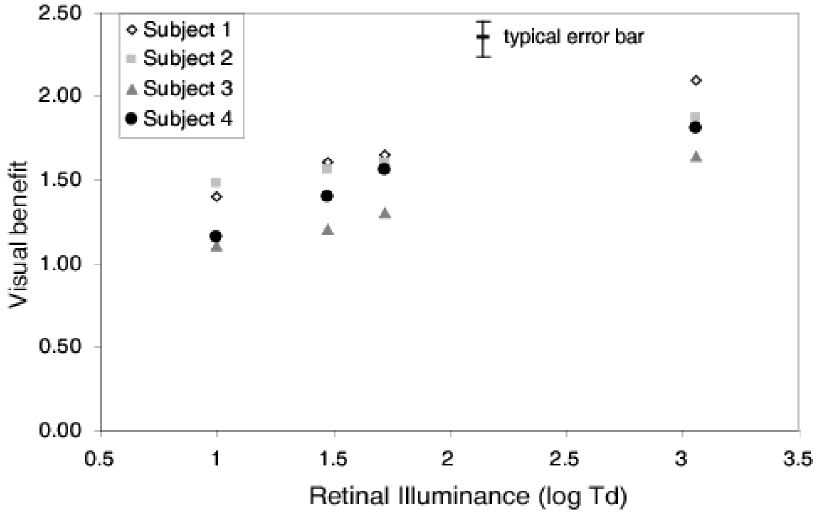

Figure 3. Visual benefit as function of retinal illuminance.

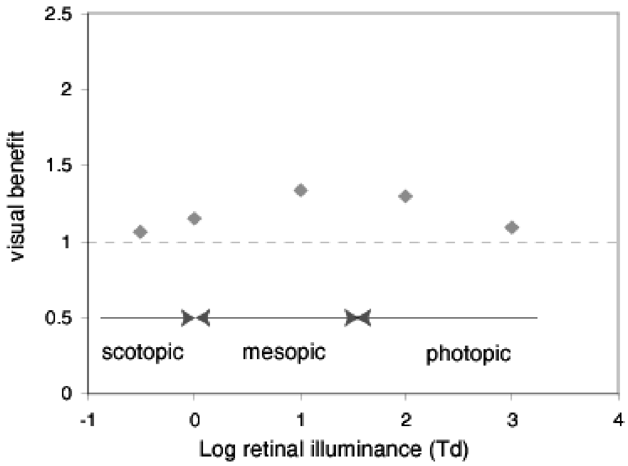

Figure 4. Example of the experimental data fitted to the natural pupil size for Subject 5.

Modelling the effects of ocular aberrations on visual performance

To gain further understanding of the fundamental limits in vision, we customized classical models of classification tasks.

Modelling methods

A classical model of discrimination task comprises the following stages: the optical and neural filtering of the object to obtain the image, the addition of noise on the image, the observation stage yielding a test statistic *t*, and the decision stage based on the value of *t* (Figure 5). Therefore, from an object, the answer of the observer can be computed.

Initially, we customized this model by including the known data on the optical filtering for each measurement performed. To represent the neural filtering, we used a generic light-dependent function (Coletta and Sharma, 1995). We defined a figure of merit *S* to assess the model-observer performance,

$$S = \sqrt{\frac{4}{\sigma^2}\frac{1}{L}\sum_{l=1}^{L}\left\|s_l - \bar{s}\right\|^2} \qquad (1)$$

with σ^2 the variance of the noise, L the number of possible alternatives and s_l the image of the l^{th} alternative. This figure of merit could be computed with and without correction of HOA to predict the visual benefit measured previously.

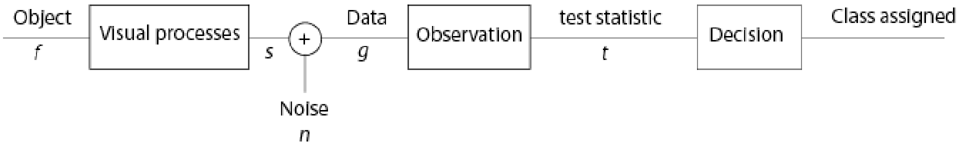

Figure 5. Schematic of a classification task model.

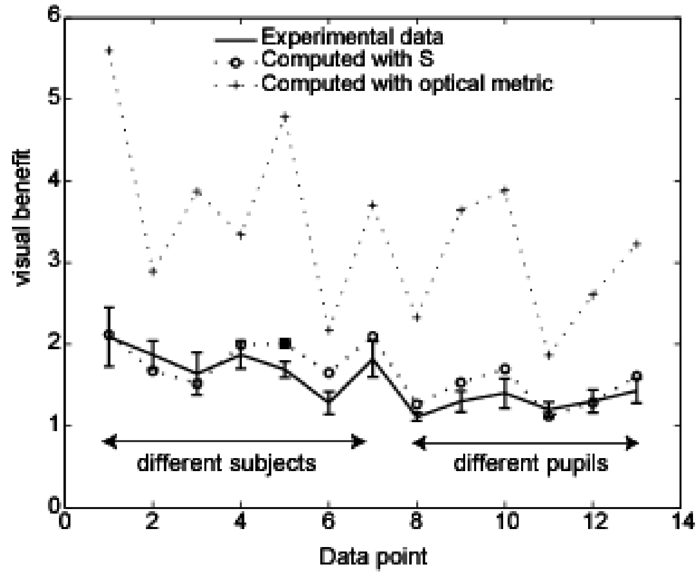

Figure 6. Comparison of the model-observer visual benefit calculated with S and the human-observer visual benefit.

Modeling results

We calculated the ratios of *S* with a conventional ophthalmic correction to *S* with a HOA correction and compared to the measured visual benefit (Figure 6). This comparison, at high light level, shows a very good agreement between the model-observer visual performance and the human-observer performance. In particular, the model provides much better predictions than metrics based only on the optical filtering of the image. The model also predicted a drop in visual benefit when the light level is decreased, although there was not full quantitative agreement (Dalimier and Dainty, 2008).

Further modeling work

In addition, we also worked on a more advanced Bayesian model of visual acuity developed by Nestares et al. (2003). The model can also be customized with information on the optical quality of the eye. For the classification stage, a different strategy is followed: the optical degradation is implicitly estimated by the Bayesian pattern recognition method.

We worked on the validation of this model with measurements of visual acuity for different optical distortions of the image. The results showed that the model could predict visual acuity for a large range of subjects and aberration amounts without any adjustment (Dalimier *et al.,* 2009). Hence it confirms that with a good knowledge of the optical formation of the image on the retina and an appropriate model of the neural stages of the visual task, reliable predictions of visual performance can be computed. Further experiments showed that when the optical quality is close to optimum, the neural parameters of the model have more importance in the predictions and could be further adjusted.

Conclusion

With the use of novel optical techniques, we investigated the limits of visual performance. In particular we showed that the correction of the small imperfections of the eye, once the main aberrations have been corrected by conventional solutions, has little impact on everyday vision. At high light level, the pupil constricts yielding a good optical quality when the neural processing is at its best. At lower light levels, the pupil dilates to increase the signal-to-noise ratio, thereby causing more optical distortions; however these distortions have little effect on the overall visual performance since the neural processing is also well decreased. Therefore the optical and neural limits of vision are well balanced to provide acceptable vision in a wide range of conditions. These experimental findings were confirmed by a customized model of the visual task. Vision models can yield good predictions of visual performance in a wide range of conditions, while also helping to understand the various stages of vision.

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