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Dynamic Image Pre-Compensation for Computer Access by Individuals with Ocular Aberrations

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Abstract— **Several image enhancement methods have been successfully used to improve the visual perception of patients with eye diseases, such as Age-related Macular Degeneration and Cataracts, on images displayed on TV and computers. However, few developments aim to enhance the visual performance of computer users with general ocular aberrations. This paper proposes an image enhancement approach based on dynamic pre-compensation for improving the visual performance of subjects with ocular aberrations, while interacting with computers. The degradation caused by ocular aberrations is counteracted through the pre-compensation performed on images displayed on the computer screen. As the ocular aberration initially measured as *a priori* information is related with a specific pupil size, real-time pupil size data are collected to recalculate and update the pre-compensation to match the corresponding aberrations. An icon recognition experiment, involving human subjects, was designed and implemented to evaluate the performance of the proposed method. The experimental results show that the proposed method significantly increased the number of icons correctly recognized, which confirmed that the dynamic pre-compensation is effective in improving the visual performance of computer users with ocular aberrations.**

I. Introduction

Nowadays people spend more and more time using computers in their daily lives and at work. Many people with severe ocular aberrations (e.g., high degree myopia, astigmatism and other high order aberrations) have difficulty in recognizing information displayed on the computer screen without the necessary vision correction. Traditionally, external methods such as spectacles or contact lenses have been widely used to correct spherical and cylindrical aberration (i.e., myopia and astigmatism). More recently, refractive surgeries (e.g., LASIK) have also become popular for vision correction. In general, these methods primarily target the correction of low order aberrations, even though high order ocular aberration correction is also an active research area, especially after the appearance of the Hartman-Shack sensor and related adaptive optics technologies [1], [2], [3]. The above means achieve vision improvement through the correction of the optical characteristics of the human eye, in general. They are not particularly designed to aid computer users. In the specific scenario of computer interaction it is also possible to perform the vision correction by the computer itself, as information to be viewed could be processed before displaying. Some technologies based on image pre-processing have been proposed previously to help low-vision patients [4], [6]. However, most of these approaches aim at improving the visual performance of patients with specific visual impairments, such as Age-related Macular Degeneration (AMD) and Cataracts [5], [6], [7], [8], but do not address the impairments of individuals with ocular aberrations in general. Different image enhancement filters, typically based on the Contrast Sensitivity Function (CSF), have been used to boost the perception quality of patients [5], [7]. However, the development of wavefront sensing devices to characterize and report the accurate ocular aberrations of the human eye has enabled other approaches that may hold more promise than the CSF-based methods.

This paper describes a dynamic image enhancement method for improving the visual performance of computer users with ocular aberrations, through pre-processing or pre-compensation of the icons presented on the computer screen. Icons are critical display elements, typically integrated in Graphical User Interfaces (GUIs). Thus, it is natural and reasonable to use images with icons as test targets in our experiments. The image pre-compensation is based on the ocular aberration of the specific computer user, which is measured with a wavefront analyzer. However, the aberrations of human eyes are not constant. Usually the ocular aberrations reported from the wavefront analyzer are related to a specific pupil size, at the time of measurement. On the other hand, the pupil size when viewing the computer screen is most likely different. This means that the ocular aberration should be recalculated and the pre-compensation should be updated with the variation of pupil size. Fortunately, several methods for adjusting ocular aberrations to changing pupil sizes have been developed [9], [10], [11]. To update the pre-compensation dynamically we used an eye tracker that monitors the pupils of the computer user in real-time. The benefits of dynamic pre-compensation were evaluated by human subject experiments.

II. Methods

A. Human Visual System

The human visual system is the combination of the optical system of the eye and the neural processing of the light information received. The neural processing stage is beyond the scope of this study. The optical infrastructure of the human eye is a complex system, which includes several sophisticated components (e.g., cornea, iris, lens, and pupil). However, if we consider it as a system, the imaging process of the human eye can be characterized by the way in which the light from a point source is projected to the retina. This is altered by the deviations from ideal spherical wavefront

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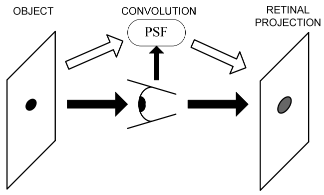
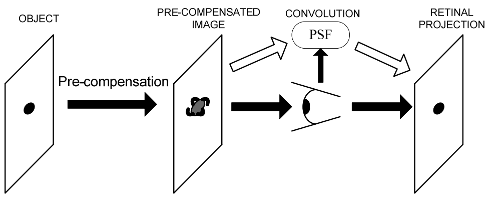


(a)



(b)

Figure 1. (a) Image formation as a convolution process; (b) Schematic of the pre-compensation method.

described by the wavefront aberration (ocular aberration) function. If significant wavefront aberrations are present, a point of light will map to a larger, diffuse area in the retina. This also explains why images perceived by an eye with ocular aberrations will seem blurred or distorted. This fact gives raise to another important function, the Point Spread Function (PSF), used to further facilitate the modeling of the human visual system. It is defined as the light distribution of a single point source on the retina. In practice, an object viewed by any optical system, including the human eye, can be represented as a two-dimensional array of point sources with variable intensity. Then, the formation of an image on the retina is described as the convolution of the array of object intensities and the PSF of the eye, as shown in Fig. 1(a).

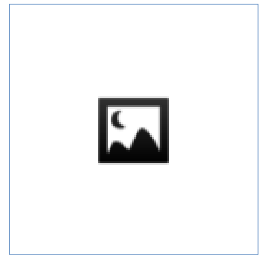
B. Image Pre-compensation Method

The image pre-compensation method discussed here pre-processes the images before they are displayed, compensating them in advance to proactively counteract the degradations caused by the ocular aberrations of different users, as illustrated in Fig. 1(b). In the context of computer interaction, all digital images to be displayed on the screen are accessible to the computer itself. This makes it possible to change or process the image data before it is presented. If the ocular aberration of the computer user that will degrade the images is known, then based on the aberration information, custom pre-compensated images can be generated for the user.

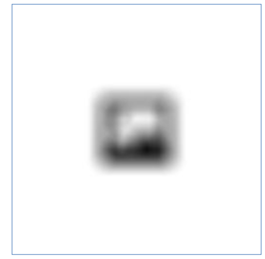
Suppose an image with intensity distribution $o(x,y)$ is displayed to be viewed by a computer user. The image is degraded due to the aberrations of the user's eye, resulting in the creation of a blurred image with intensity $i(x,y)$ on the retina. The PSF of the user's eye is derived as $psf(x,y)$ from the wavefront aberration measured. As mentioned before, the viewing process can be described as a convolution:

$$i(x,y) = o(x,y) * psf(x,y) \qquad (1)$$

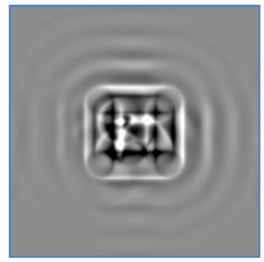
The optical transfer function (OTF), another useful function for describing visual performance, is calculated by applying the Fourier transform to the PSF as:



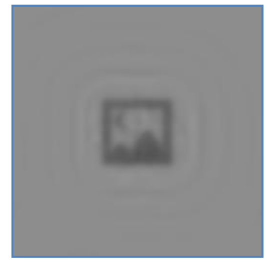
(a)



(b)



(c)



(d)

Figure 2. (a) One icon for display; (b) What a user with -6D spherical aberration perceives when viewing (a); (c) Icon after Pre-compensation; (d) What a user with -6D spherical aberration perceives when viewing (c).

$$OTF(u,v) = \mathcal{F}\{psf(x,y)\} \qquad (2)$$

The modulation transfer function (MTF) could be derived as the modulus or magnitude of the complex-valued OTF:

$$MTF(u,v) = |OTF(u,v)| \qquad (3)$$

Based on linear system theory, the multiplication that represents equation (1) in the frequency domain can be manipulated to derive the pre-compensated image $c(x,y)$ from its representation in frequency domain, which is:

$$C(u,v) = \frac{O(u,v)}{OTF(u,v)} \qquad (4)$$

However, equation (4) is not practical since errors in the measurement of the ocular aberrations will be greatly amplified when the value of $OTF(u,v)$ is close to zero. To reduce the impact of this drawback, the Wiener filter is used here with the regularization parameter K, which suppresses the extreme amplification of the errors mentioned above:

$$C(u,v) = \frac{O(u,v)}{OTF(u,v)} \frac{MTF(u,v)^2}{(MTF(u,v)^2 + K)} \qquad (5)$$

Accordingly, the pre-compensated image $c(x,y)$, which is the one actually shown to the user on the screen, could be calculated by inverse Fourier transform of the result obtained from (5).

Fig. 2(b) shows an example of what a user with -6D spherical aberration would perceive when viewing the icon shown in Fig. 2(a). If the original icon is pre-compensated, as explained above, on the basis of the user's ocular aberration, the result is as shown in Fig. 2(c). The simulation result in Fig. 2(d) shows what the same user will perceive when viewing the compensated image (Fig. 2(c)). From Fig. 2(d), we find that the perceived shape and edges of the pre-compensated icon are much sharper than those of Fig. 2(b), which confirmed the expected results for the pre-compensation method in simulation and its potential to be used to help computer users with ocular aberrations. A drawback of the method, however, is the reduction of the perceived image contrast when viewing the pre-compensated icon. This is because of the intensity range limitations of the display device [12].

C. Dynamic Pre-compensation

The pre-compensation method requires knowledge of the ocular aberration *a priori*. The aberration is often defined mathematically using a family of polynomials. Among them, a popular polynomial set used is the Zernike polynomials. The wavefront aberration can be defined as:

$$W(r,\theta) = \sum_{i=0}^{\infty} c_i Z_i(r,\theta) \quad (6)$$

where c_i represent the Zernike coefficients and $Z_i(r,\theta)$ represent the corresponding Zernike polynomials. In practice, the wavefront analyzer used in our work also reports the measured aberration as a set of Zernike coefficients. However, the measured Zernike coefficients are only related to the specific pupil size of the eye at the time of wavefront measurement. This raises a concern for our pre-compensation method since the pupil size of the human eye is not constant. A well known fact is that the pupil size varies according to the illumination conditions. Thus, the pupil size during computer use can be different from the size at the time of wavefront measurement. Specifically, considering the fact that we always measure the aberration under relatively dark conditions, the pupil size difference under these two cases could be quite large. This means that if we perform compensation based on the measured ocular aberration directly, the pre-compensated image may not be suitable for the computer user as the ocular aberration used to generate the compensation is mismatched. Fortunately, if the aberration data for a large pupil is available (as is our case), methods have been developed to derive the new aberration corresponding to a new pupil size, typically a smaller one.

The basic idea of this conversion is that the same area of a surface will be described by different sets of Zernike coefficients if a different aperture radius is used to find the coefficients. Campbell [11] developed a method to find a conversion matrix $[C]$, which will convert one Zernike coefficient vector c associated with an original aperture radius to another Zernike coefficient vector c' associated with a new aperture radius by multiplication:

$$c' = [C]c \quad (7)$$

The conversion matrix $[C]$ is derived as:

$$[C] = [P]^T[N]^{-1}[R]^{-1}[\eta][R][N][P] \quad (8)$$

where the “T” and “-1” superscripts mean matrix transposition and inversion respectively. $[P]$ represents the permutation matrix, $[N]$ indicates the normalization matrix, $[R]$ indicates the weighting coefficient matrix and $[\eta]$ indicates the powers of ratio matrix, which is determined by the ratio of original aperture size and the new aperture size.

Since the pupil diameter may vary even within a viewing session, it is necessary to use an eye-tracking system to continuously monitor the pupil of the user. This is discussed in the next section.

III. Experiment

The objective of this research is to improve the visual performance of those computer users with ocular aberrations. Thus, in order to evaluate the visual performance enhancement achieved by the dynamic pre-compensation method proposed, human subject tests were implemented to test the ability of the experimental subjects to correctly recognize the icons displayed.

A. Subjects

Ten subjects aged from 20 to 29 years (5 of them were male and 5 of them were female) participated in our experiment. The subjects were mainly college student volunteers. Most of them have high degree spherical or cylindrical aberration or both. The spherical aberrations of subjects range between -3.24 and -10.34D (-6.36±1.99D) and the cylindrical aberrations of subjects range between -0.22D and -2.03D (-0.76±0.48D). All the subjects performed the experiment with both eyes. Thus, 20 eyes were tested in total. The experimental protocol was approved by the university IRB committee, in advance. Written consent was signed by all the subjects before the experiment.

B. Experiment Environment

Recognition of the computer output is a critical step required for successful interaction with computers. Thus, a recognition task is an objective way to evaluate the visual performance of computer users. A Visual C# computer interface was designed to present the test images to the subjects and to automatically record all the experiment data measured in a database. Before the test, the participants were required to undergo an ocular aberration measurement through a wavefront analyzer (COAS-HD, Wavefront Sciences). For dynamic pre-compensation, an eye tracking system (T60, Tobii) was used to collect the real-time pupil data of the subjects. The Tobii T60 eye tracker, provides pupil size measurements at a rate of 60 Hz and is integrated in a 17-inch TFT computer monitor, where the test images were displayed.

C. Experimental Design

In the experiment, the subject was required to sit in front of the computer to identify the images displayed. The distance between the subject and the computer screen was set to be 25 inches. As the aberrations of two eyes are commonly different, the experiment was designed for monocular vision. Thus, one eye was covered by an eye patch while the other eye was being tested. The subjects were not allowed to use glasses, contacts or other vision correction devices in the experiment. All the compensated images were generated in real time on the basis of real-time pupil size measurements and previously measured large-pupil (low illumination) ocular aberration. The images used for test were 8 commonly used icons, including Copy, Document, Folder, Email, Picture, Print, Save and Delete, as shown in Fig. 3. Each subject was shown the icons before the test and asked to memorize their names. Two versions of each of the 8 icons were used, one small (48 pixels) and one large (72 pixels). Each subject was presented with the icons (small and large) in two types: original (uncompensated) and dynamically

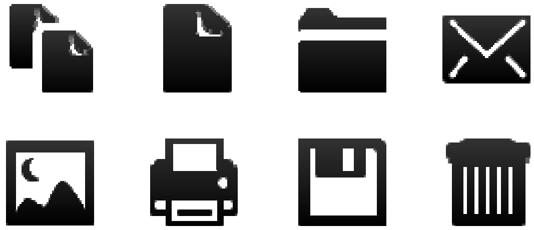


Figure 3. Eight icons used in the experiment (Copy, Document, Folder, Email, Picture, Printer, Save and Delete).

pre-compensated. That is, for each factorial condition of size and compensation, 8 different icons were presented to the subject in random sequence and every icon was presented once, and only once, for 3 seconds. Thus, 32 icons in total were presented to each eye of each subject.

IV. RESULTS

A two way ANOVA with repeated measures was utilized to analyze the results of the experiment. The independent factors of this experiment were icon type (with or without pre-compensation) and icon size (small or large). The dependent variable was the number of correct recognitions made, in every set of 8 icons.

From the ANOVA results, we found that the difference between icons with pre-compensation and icons without pre-compensation was significant, $F(1,19) = 22.29$, $p<0.01$. The group mean of correct recognition number increased from 4.60 (icons without pre-compensation) to 6.15 (icons with pre-compensation). This indicates that the subjects experienced significant improvement of visual performance after our method was applied, which boosted the accuracy of their icon recognition process. There was a significant difference between small size icons and large size icons, $F(1,19) = 48.99$, $p<0.01$. The group mean of correct recognition number had an increase from 4.45 (small size) to 6.30 (large size). This is quite intuitive since the identifying features in large icons are less deteriorated by a given level of ocular aberration. Fig. 4 shows the clustered bar graph of correct recognition means for original and pre-compensated icons, in the categories of small size and large size.

The interaction between the icon size and icon type was also found to be significant $F(1,19) = 5.15$, $p<0.05$. The number of correct recognitions was smaller for small icons and larger for large icons. This may be because the small size icons are more vulnerable to blurring effects, while large size icons can still be identified by some subjects, in spite of the fact that they are perceived with some level of blurring.

V. CONCLUSION

This paper proposes an image enhancement method to improve the visual performance of computer users with significant ocular aberrations. The method is based on the measured ocular aberrations of each specific computer user. It implements dynamic pre-compensation, based on the continuous real-time collection of pupil data. The method was evaluated with human subjects through an icon recognition experiment. Statistical analysis showed that the number of correct icon recognitions with pre-compensation is significantly larger than without pre-compensation. The

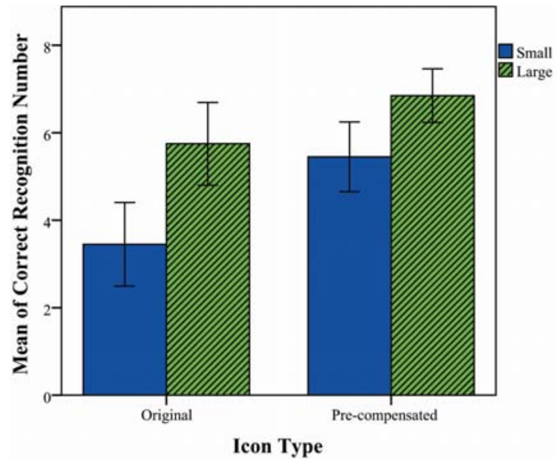


Figure 4. Mean of the correct recognition number for original and pre-compensated icons.

analysis also showed that the proposed method aids the recognition of small icons more than large icons.

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