Evaluation of Dynamic Image Pre-Compensation for Computer Users with Severe Refractive Error

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ABSTRACT
Visual loss and blurring impedes the efficient interaction between the computers and its end users. Visual problems can be caused by eye diseases, severe refractive error or combined in most cases. Several image enhancement methods based on contrast sensitivity have been used to help people with eye diseases (e.g., Age-related Macular Degeneration and Cataracts), whereas few researches were designed for people with severe refractive errors. This paper described a new pre-compensation method to relieve the visual blurring caused by the severe refractive errors of specific computer user. It preprocesses the pictorial information through dynamic pre-compensation ahead, aiming to present customized images on the basis of the ocular aberrations of specific computer user. The new method improves the previous static pre-compensation method by updating the ocular aberration with pupil variations in real-time. The real-time aberration data enable us to generate more suitable pre-compensated image, as the pre-compensation model is updated dynamically. One empirical study was conducted to evaluate the efficiency of the new pre-compensation method, in the form of icon recognition test. From the results of statistical analysis, we found that participants gained significantly higher accuracy ratio to recognize the icons with dynamic pre-compensation, comparing with the original icons. The accuracy is also significantly boosted when the icons were processed with dynamic pre-compensation method, comparing with static pre-compensation method. In addition, the subjective feedbacks from participants exhibited consistency with the analysis results, confirming the efficiency of the dynamic pre-compensation method.

Categories and Subject Descriptors
K.4.2 [Social Issues]: Assistive technologies for persons with disabilities

General Terms
Performance, Design, Experimentation, Human Factors

Keywords
Refractive error, image pre-compensation, image enhancement, ocular aberration, icon recognition.

1. INTRODUCTION
As one of common causes of visual impairments, the refractive error (e.g. myopia, hyperopia and astigmatism) leads to blurred vision of human eye, in more or less degree depending on its severity. Myopia affects more than 30.5 million Americans age 40 or older and approximately 25% of American adults require some form of corrections to see clearly beyond an arm’s length [16]. Although refractive error seldom causes the blindness, it does produce substantial visual loss that impacts the learning and working efficiency as well as facility of daily life [5, 25].

Regarding the computer accessibility, the blurring caused by refractive error impedes the efficient interaction between the computer and its users. The refractive error can be corrected by spectacles, contact lenses or refractive surgery (e.g., LASIK) in most cases. However, not all of the visual losses can be relieved through these methods. For those people with eye diseases (e.g., cataracts, glaucoma, macular degeneration), the benefit acquired from spectacles or contact lenses are limited. The prevalence of these diseases usually increases with aging, combined with refractive errors [16, 18, 24]. Besides, general spectacles and contact lenses are not able to correct high order aberrations, rendering the correction of high order ocular aberration to be one of the most active areas in adaptive optics community [8, 10, 17, 22]. Therefore, it is still meaningful to seek new approaches to facilitate computer accessing for different visually impaired people.

Although the researches in this area are still few to date, several image enhancement techniques have been developed and published. In the early studies, heuristic and empirical filters were used to improve the text reading ability of visually impaired people in the form of digital images [9, 13, 14]. Similar techniques were also used to facilitate face recognition on monitors for people with central visual field loss [19]. Other approaches include thresholding and edge highlighting upon original images for display [15, 20]. Most of these studies primarily focus on the contrast enhancement of pictorial information presented. Thus, the enhancements applied are based on contrast sensitivity function (CSF), which reflects contrast differentiation ability in different spatial frequencies but not the optical characteristics of the eyes. Generally, these methods are not generic since the amount of enhancement needs to be tailored on the basis of the preferences of participants.

Alonso et al. [1, 2] proposed a new method to neutralize the visual degradation, by which all the images displayed on the screen were pre-compensated in advance based on the ocular aberration of specific computer user. Although this method did acquire improvements of visual performance, the effect was not as large as expected. This was most likely attributed to the mismatch between the measured ocular aberration that is used to generate the pre-compensation and the ocular aberration at the time of
actual viewing. To address this limitation, we improve the previous static pre-compensation method to be dynamically adjusted and ensure the ocular aberration updating in real-time. The optics of human eye is not static even in steady viewing environment but fluctuate over time. The fluctuations are not large under normal circumstances hence produce little impact on vision. However, the pupil size variations, primarily caused by the changes of illumination condition, do produce considerable impacts on the aberration of the eye. Thus, the pupil data were collected through an eye tracking system in our study, for resizing the ocular aberration from the one measured through Hartmann-Shack sensor to new one dynamically. To validate the efficiency of our method, participants were recruited to perform the icon recognition task on the computer screen with or without applying dynamic pre-compensation respectively. For comparison, the same task was also performed when applying the static pre-compensation.

2. BACKGROUND

2.1 Human Visual System

Image formation on retina is the first step in the human’s visual process. The optical performance of the human eye is mainly determined by the cornea, iris, pupil, and lens. Various eye diseases or problems are caused once dysfunctions exist in these components. Even though the human eye is quite complex, if we consider these components as a whole, the imaging process of human eye can be simply described as the intensity distribution of viewed object the retina according to the optics of the eye.

2.2 Ocular Aberration

Based on the wave theory, how the intensities of external object are distributed on the retina is determined by the wavefront characteristics of the eye. The wavefront aberration function of human eye (ocular aberration) is defined as the difference between the actual aberred wavefront and the ideal spherical wavefront when light comes into the eye. The ocular aberrations of the entire eye are combinations of the aberrations primarily from cornea and lens. All human eyes have more or less degrees of aberrations and any ocular aberration will degrade the resulting retinal image. Refractive error is mainly caused by low order aberrations, including spherical error (e.g., myopia, hyperopia) and cylindrical error (e.g., astigmatism, Presbyopia). The low order aberrations contribute most of the degradation to the vision quality [7].

Benefiting from the development of Shack-Hartmann sensor, measurement of ocular aberration becomes readily available. It is usually reported as a set of Zernike polynomials and coefficients, through which the corresponding ocular aberration \( W(r, \theta) \) can be reconstructed by:

\[
W(r, \theta) = \sum_{\ell=0}^{\infty} z_{\ell} P_{\ell}(r, \theta)
\]

where \( z \) represent the measured Zernike coefficients and \( P(r, \theta) \) represent the corresponding Zernike polynomials in polar form. Note that the Zernike polynomials are related with a pupil radius \( r \).

2.3 Formation of Retinal Image

The process of image formation on retina can be further simplified by introducing Point Spread Function (PSF), which is the image formed by a single point source on the retina. Considering the object viewed by the eye as a two-dimensional array of point sources with variable intensities, hence, the formation of an image on the retina can be described as the convolution of the intensity array and the PSF of the eye (Figure 1). This process is shown mathematically as:

\[
i(x, y) = o(x, y) * PSF(x, y)
\]

where \( o(x, y) \) is the ideal image of the viewed object and \( i(x, y) \) is the retinal image attained by convolution. In our study, \( i(x, y) \) is the original image for display, in the form of an intensity matrix. For computation simplicity, Fourier transform is always performed on PSF to generate Optical Transfer Function (OTF):

\[
OTF(u, v) = \mathcal{F}(PSF(x, y))
\]

and Modulation Transfer Function (MTF) that is the magnitude of the complex-valued OTF:

\[
MTF(u, v) = |OTF(u, v)|
\]

3. METHODS

All the elements (e.g., pictures, texts, icons) displayed by the modern computers can be represented in the form of digital images. Thus, the computer, as one side of interaction with its user, is capable of preprocessing the images before display. Most assistive techniques based on image preprocessing, including our image pre-compensation method, are built on this premise.

Due to the visual degradation caused by the ocular aberrations, most computer users with severe refractive errors encounter difficulties to view images without processing, presented on the screen. This triggers the intuitive idea to present images that are particularly designed or modified instead. The idea of image pre-compensation is similar with image restoration in some degree. As a priori knowledge of degradation (or part of it) needs to be known in the process of image restoration, the ocular aberration of the specific computer user is also required at first to produce customized pre-compensation. In practice, ocular aberration can be readily measured by an aberrometer. Even so, the image pre-compensation discussed here has substantial difference with image restoration. Instead of post-processing the degraded image to recover it from degradation, the image pre-compensation method degrades the images to be viewed in particular pattern, aiming to neutralize the blurring caused by the ocular aberration of specific computer user.

3.1 Static Image Pre-Compensation

Unfortunately, most of algorithms successfully used in image restoration are not effective anymore to be used by the image pre-compensation, as the images processed will be “blurred” again at viewing. One effective method is Inverse Wiener Filtering (IWF), as introduced in details in [17].

Applying the basic form of Inverse Wiener Filtering, the pre-compensated image \( c(x, y) \) can be generated in the spectral domain by:
In the equation above, $O(u, v)$ is the Fourier transform of original image for display. $K$ is the regularization parameter, which are used to suppress the ill amplification of ocular aberration errors especially when the value of $\text{OTF}(u, v)$ is close to zero at some frequencies.

The generated pre-compensated image $c(x, y)$ is the one actually presented to be viewed, with particular distortions designed to be “blurred” by the user’s eye. Figure 2(b) shows an example of what a computer user would perceive when viewing the icon shown in Figure 2(a) by simulation. It is generated based on an ocular aberration with -6D spherical error. Figure 2(c) is the image produced after applying pre-compensation. The simulation result in Figure 2(d) shows what the same user will perceive when viewing the pre-compensated image (Figure 2(c)). From it, we find that the perceived shape and edges of the pre-compensated icon are much sharper than Figure 2(b), although its overall contrast has been reduced. The simulation results show the feasibility of the image pre-compensation as a potential way to relieve the visual blurring caused by refractive error.

### 3.2 Variation of Ocular Aberration

The validity of above static pre-compensation is built on the assumption that the measured ocular aberration is the same with the ocular aberration at the time of viewing the image. In practice, this assumption is not always met as the ocular aberration may vary with light condition changing, accommodation and other psychophysical factors. Even under steady viewing conditions, the optics of human eye is not constant but exhibiting temporal instability in the form of fluctuation [11, 21]. The magnitude of these fluctuations are approximately 0.03-0.5 diopters and with frequencies up to 5 Hz [4]. Recent researches also show that similar fluctuations exist in not only defocus error but also other high order aberrations [11, 12, 21]. Since our pre-compensation method is targeting to the population with severe refractive error, it is reasonable to disregard the ocular aberration variations caused by this kind of fluctuations.

However, the change of ocular aberration caused by pupil variation cannot be ignored. It is well known that the pupil size varies with the illumination conditions. Thus, the pupil size of one computer user sitting in front of computer is likely to be different from the size at the time of wavefront measurement. Specifically, considering we always measure the aberration under relatively dark condition, the pupil size difference under these two cases can be quite large. As we introduced in last section, the ocular aberrations measured by aberrometers are reported as a set of Zernike coefficients. In practice, these coefficients are related with a specific pupil radius. This means once the pupil size changes, the aberration will also be changed correspondingly and needs to be recalculated. Thus, if we perform pre-compensation based on the measured aberration directly, the pre-compensated image may not be suitable as the aberration data used to generate the compensation is changed considerably. This fact requires us to update the ocular aberration of specific computer user along with the pupil size variations. Fortunately, if the aberration data for a large pupil is available, methods have been developed to derive the new aberration according to a new and smaller pupil size, typically a smaller one [3, 6, 23].

### 3.3 Dynamic Image Pre-Compensation

In order to resolve the aberration mismatch problem, we improve the static image pre-compensation to be dynamic, through monitoring the pupil data and updating the aberration in real-time. The conversion method used in our study is proposed by Campbell [3]. Its basic idea 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. Through a conversion matrix $C$, this approach is able to convert one Zernike coefficient vector $c$ associated with an original pupil radius to another vector $c'$ associated with a new pupil radius by:

$$c' = Cc$$

The conversion matrix $C$ is dependent on the ratio of original pupil size and the new pupil size, and the algorithm for its calculation is detailed in [3].

To support our dynamic pre-compensation method, each specific computer user is required to take the aberration measurement through an aberrometer only once. The measurements were conducted under dark environment to assure the pupils of participants are dilated. This is necessary since the ocular aberration is only expected to be resized from a large pupil size to a small pupil size. If aberration data was collected with a relatively small pupil size (under bright illumination condition), then deriving the aberration corresponding to another large pupil size was not reliable, as it contained the aberration data which was not available in the measured aberration. The measured aberration data, including the “base” pupil diameter, will be stored in a file with identity names. Thus, computer users assisted by our system need to log in first for proper pre-compensation.
Figure 3. Schematic of the dynamic image pre-compensation system.

In practice, the real-time pupil data used to update the aberration can be collected by an eye tracking system. Detailed information of it will be introduced in next section. Figure 3 illustrates the schematic of our dynamic image pre-compensation system.

3.4 Side Effects of Pre-Compensation

Although the IWF achieved good performance in recovering the shape of image, it has two major side effects, which can be observed in the Figure 2(d).

The first one is the ringing artifacts, most pronounced around the regions with abrupt intensity transition. Regularization is always required by the process of Wiener Filtering in order to suppress high frequency error. As a tradeoff, the regularization error is distributed across the whole frequency spectrum, as shown in equation (6), leading to the ringing artifacts in the image. In the real application other than the simulation, there are always errors between the model used to generate the pre-compensation and the actual model. This will make the ring artifacts more problematic.

The second one is the remarkable contrast decrease of perceived image after pre-compensation. In general, the IWF behaves like a high pass filter. Thus, the pre-compensated image usually has a wider range than the original image, even involving negative values. Nevertheless, regular display devices (e.g., LCD) only have limited intensity scales. Thus, the intensity values need to be shifted and scaled before the pre-compensated image can be displayed. The downscaling in this process will narrow the range of intensities, causing part of the contrast lost.

4. EVALUATION

The objective of this research is to relieve the blurred vision of those computer users with severe refractive errors, hence facilitating their daily computer access. The evaluation of our dynamic image pre-compensation method was conducted through an empirical study. Our evaluation has two major assumptions. The first one is that the dynamic pre-compensation method did improve the vision quality of participants, comparing with the circumstance under which the images were presented without any processing. The second one is that the dynamic pre-compensation is superior to the previous static pre-compensation. If the assumptions are confirmed, the evaluation will also assess how much improvement was achieved.

Our study was designed on the basis of an icon recognition task. As one of the most popularized elements of computer presentation, icons are widely used in graphic user interfaces to facilitate the interaction between human and computers. Correct and efficient icon recognition is required for many computer-based tasks. Thus, it is appropriate that the visual performance was evaluated through the accuracy of icon recognition on the computer screen.

As the pre-compensation is generated based on the specific ocular aberration, the pre-compensation for two eyes (even though they belong to the same user) should also be different. Thus, the icon recognition test in our study was based on the monocular vision of participants.

Figure 4. Refractive errors of 20 participants (40 eyes) in the study.

4.1 Participants

Twenty participants were recruited to take part in our icon recognition based study with rewards. The participants ages ranged from 20 to 33 years old (M ± SD). Thirteen of them were male and seven of them were female. Most of them are undergraduate or graduate students, with high degree spherical or cylindrical errors, or with both. The spherical aberrations of participants ranged between -3.24 and -10.34D (-6.17±1.63D) and the cylindrical aberrations of subjects ranged between -2.22D and -2.44D (-0.88±0.58D). Detailed information of participants’ refractive errors is shown in Figure 4. All the participants performed the same icon recognition test with both the left eye and right eye. Thus, 40 eyes in total were tested in the study. Written consent was signed by all the participants before the test.
4.2 Instruments and Environment
Before the icon recognition test, initial ocular aberrations of participants were measured through an aberrometer (COAS-HD, Wavefront Sciences). The reported Zernike coefficients were up to 6th orders, stored with a specific base pupil diameter. Participants were not allowed to wear glasses or contacts during the tests.

The icon recognition tests were performed on an interface developed by Visual C#, upon which the icons were presented. The test data of participants was categorized and recorded in a database in the background for post analysis.

In order to monitor the pupil variations of participants, an eye tracking system (T60, Tobii) was used to collect the real-time pupil data of the participants. The Tobii T60 eye tracker is able to provide pupil size measurements at a rate of 60 Hz. In our study, only the pupil diameter data were considered. The eye tracker is integrated in a 17-inch TFT computer monitor, which is also used as the display device in our study.

4.3 Design and Procedures
During the icon recognition tests, the participants were instructed to sit in the front of the computer monitor. The distance between the participant and the computer screen was fixed to be 25 inches. Once the participants were sitting in a comfortable position, they were not permitted to move forward or backward to change the distance. As the test was based on the monocular vision, one eye was covered by an eye patch while the other eye was being tested. The tests were conducted under office light condition assuring the pupil size was smaller than the base pupil size. After completing the test of one eye, the participant was allowed to take a 5 minutes break for resting the eyes.

The icons selected for test were 8 common icons, including Copy, Document, Folder, Email, Picture, Printer, Save and Delete (Figure 5). As the visual acuities vary with participants, we created two versions of icons with two different sizes. The small version icons were with 48 pixels (side) and the large ones were with 72 pixels (side). All icons were black and white, without any color information. The participants were required to memorize the names of these eight icons before the test. Reviewing the icons was not permitted once the test started.

For comparison, icons would be presented under three circumstances, that is: original icons (Original), static pre-compensated (SPC) icons and dynamic pre-compensated (DPC) icons. In the case of dynamic pre-compensation, each icon was processed in real-time on the basis of the monitored pupil size at the time when the icon was displayed. The icon would not be updated anymore until the next icon was requested. The icons were presented in random sequence one by one for each combination of icon type and icon size. Each icon was presented only once. Thus, there were 8(icons)×2(sizes)×3(methods)=48 trials for each eye’s evaluation session.

During the test, the participants were asked to give out their answers by speaking after viewing specific icons. Based on the answers, we recorded the numbers of correct recognitions. Aside from this, the participants did not need to do any other operations. In previous experimental sessions, we had found that participants would get tired after prolonged monocular viewing. Therefore, in this study, we presented each icon for only 3 seconds. After that, the icon would disappear from the screen. This also removed the noneffective recognitions made by the participants (using too much time).

Figure 5. Eight icons used in the icon recognition test (Copy, Document, Folder, Email, Picture, Printer, Save and Delete).

Our evaluation used repeated measures factorial design with two factors: the icon type, with three levels (original, SPC and DPC) and the icon size, with two levels (small and large). The dependent variable was the number of correct recognitions made by the participants, which could range from 0 to 8.

A two way ANOVA (repeated measures) analysis was conducted to test the effects of different pre-compensation methods and icon sizes on the recognition accuracy. We also investigated the interactions between pre-compensation method and icon size in the evaluation.

4.4 Results
We found that the main effect of icon type on the recognition accuracy was significant, \( F(2,78) = 48.52, p<0.01 \). This meant that applying pre-compensation did impact the recognition accuracy of participants in the tests. As shown in Figure 6, the means of correct recognitions are 3.98, 3.20 and 5.58, corresponding to the three different types of icon (original, SPC and DPC) respectively. By applying dynamic pre-compensation to the original icons, the mean of correct recognition number increased from 3.98 to 5.58 with the average accuracy ratio increasing from 49.8% to 69.8%. Not surprisingly, the difference between dynamic pre-compensated icons and original icons was significant, \( p<0.01 \).

Comparing with SPC icons, DPC icons had an increase on the average correct recognitions, from 3.20 to 5.58 (the accuracy ratio increased from 40% to 69.8%). The difference between SPC icons and DPC icons was also significant, \( p<0.01 \). It was noted that the
average correct recognition number with static pre-compensation was lower than the original icons.

As we expected, there was a significant effect of the icon size on the accuracy, $F(1,39) = 153.54, p<0.01$. The mean of correct recognitions increased from 3.42 (small size) to 5.08 (large size). The interaction between the icon type and icon size was not significant, $F(2,78) = 2.21, p = 0.116$.

4.5 Explanation of Results

After the icon recognition test, subjective feedbacks from participants were also collected, combining with the recorded accuracy, to evaluate their visual performance in the tests.

The significant effect between DPC icons and original icons validates that the image dynamic pre-compensation method did improve the visual performance of participants. Consistently with the test results, most of participants (16 of 20) gave the feedback that they perceived much sharper shapes of icons while dynamic pre-compensation was applied, than the original icons.

The increasing recognition accuracy ratio gained by DPC icons, comparing with SPC icons, validated the superiority of dynamic pre-compensation method to static pre-compensation method. Besides, almost all participants (18 of 20) preferred the DPC icons more than the SPC icons and the rest two reported equal visual perception. These results were consistent with our assumption, as the SPC icons were generated based on the measured ocular aberrations only. For those two participants claimed perceiving equal vision quality with SPC and DPC icons, it is found that their base pupil sizes were also close to the recorded pupil sizes during the recognition tests, explaining their reports reasonably.

Surprisingly, the average correct recognition of SPC icons was lower than the original icons. Many participants reported they viewed abnormal distortions and obscure edges on the SPC icons. This could be explained by the fact that, for most participants, the pupil diameters collected to update the aberrations were much smaller than the base pupil size, producing images with ill-suited pre-compensation. The degradations caused by ill-suited pre-compensation were probably even more disliked than the blurring of original icons. One typical record of pupil variations is shown in the Figure 7, in which the pupil diameters of one participant, used to update the aberration data during the test, are curved, comparing with the base pupil parameter related with the original measured aberration data.

The reason for the increased accuracy ratio from small size icons to large size icons is quite intuitive, as icons with large size are more easily recognized. The analysis show there is no significant interaction between icon type and icon size, which indicates that the pre-compensation method generates same effects to small icons and large icons. For the DPC icons, it implies that the dynamic pre-compensation method boosted the recognition accuracy of small icons and large icons identically.

5. Improving the Method

Even though DPC icons provided the best recognition accuracy in our study, the vision quality after applying the dynamic pre-compensation was still far away from satisfying. One survey was conducted regarding the factors that most impeded the acquisition of desired visual perception, only to the icons when dynamic pre-compensation was applied. As shown in the Figure 8, 55% of participants believed it was low contrast of pre-compensated icons; 25% of answers were ringing artifacts; 20% of answers were other factors (e.g., abnormal blurs and edge overlapping). The results of this survey implicate that our dynamic image pre-compensation method can be greatly promoted if the problems of low contrast and ringing artifacts are relieved.

Both the low contrast and the ringing artifacts problems are introduced by the process of Inverse Wiener Filtering. The contrast reduction is substantially caused by the wide range of intensity value after pre-compensation, while the ringing artifacts are due to the spreading of regularization and modeling errors. Even though there are no evidences yet show these two problems are contradicted and require trade off, we do believe they are associated or coupled in some degree. Based on the results of the survey, probably highest promotion can be obtained by finding a way to increase the contrast after pre-compensation. One possible way is restricting the pre-compensation within a particular range of frequency spectrum, while losing part of high details as trade off.

6. CONCLUSION

Computer users with severe refractive errors always encounter difficulties to view the pictorial information displayed without vision correction. Traditional means to resolve this problem include spectacles, contact lenses and refractive surgery. This paper described a new approach to preprocess the images through dynamic and customized pre-compensation, aiming to relieve the visual blurring caused by the ocular aberrations of specific...
computer user. The dynamic pre-compensation method improves the previous work, in which the pre-compensation is generated based on fixed model, by taking account of the dynamic characteristics of the human eyes. As the ocular aberration changes with pupil size variations, we updated the aberration data used to calculate the pre-compensation according to the real-time pupil data monitored through eye tracking. In order to evaluate the performance of our method, an empirical study was conducted with 20 participants in the form of icon recognition test. We found that the participants achieved boosted recognition accuracy when the icons with dynamic pre-compensation were presented, significantly higher than the icons with static pre-compensation as well as the original icons without any processing. The subjective feedbacks of participants confirmed the analysis results.

Even though the benefits attained from our method is still far away from practical application, the encouraging results from our study justifies that the dynamic image pre-compensation is a promising way to improve the vision quality of computer users with visual problems. Based on the simulation results and feedbacks from participants of the test, the performance of our method is mostly limited by two major problems (low contrast and ringing artifacts). Relieving these two problems requires further exploration of new pre-compensation algorithm other than Inverse Wiener Filtering.

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8. REFERENCES


