

# Development and Evaluation of a Custom Display Compensation Method for Computer Users Based on Individual Visual Characteristics

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## Abstract

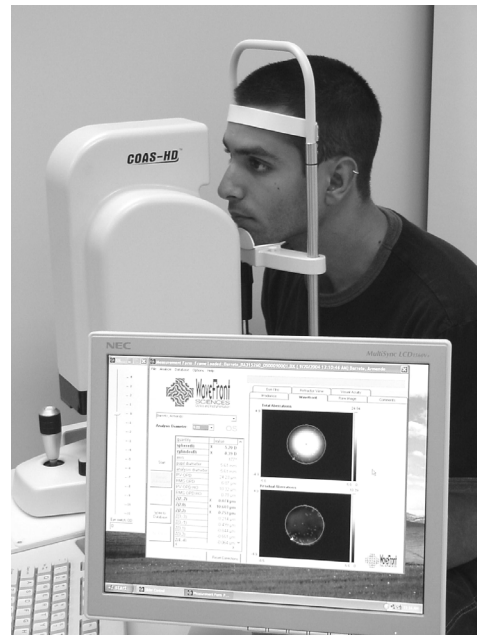
*In this paper, we present the development and evaluation of a custom on-screen image precompensation algorithm designed to match the visual capabilities of each user, to allow efficient access to images displayed on the screen of the computer. The method uses the characterization of the optical system in the eye of the computer user, which is obtained through a Wavefront Analyzer, to modify the display images in a way that will counter the distortion that they will experience in the eye of the user. An empirical evaluation, involving 20 subjects with varying degrees of visual dysfunction confirmed that the method used for precompensation provides a significant increase in retinal image quality for users that have some visual aberration present in the optical systems of their eyes. The methodology presented here represents a step forward in the direction of adaptable computer interfaces, which may represent the future in customization of human-computer interactions.*

## 1. Introduction

Graphical User Interfaces (GUIs) for computers have evolved to suit the needs of most users. However, they have, in many cases, disregarded the needs of a subset of users with visual aberrations. Furthermore, there are some kinds of visual afflictions (e.g., Keratoconus) that are not overcome by classical means of GUI enhancement, such as screen magnifiers. For some of these afflictions, other forms of enhancement beyond magnification may be needed. In particular, given the degree of potential variability in the type of distortion that may be present in the visual system of each individual computer user with visual dysfunction, it would be highly desirable to be able to provide a customized solution to each of them.

We have previously introduced a custom method of on-screen image precompensation that attempts to display computer images that match the known visual

profile of a given user, countering his/her visual dysfunction [1]. The method only requires knowledge of the user's particular visual aberration, as characterized by a wavefront analyzer. Fig. 1 shows the Wavefront Sciences, Inc. COAS-HD unit used to obtain the wavefront aberration functions for the subjects involved in our research.



**Figure 1. COAS-HD Wavefront Analyzer**

The goal of this paper is to present an overview of the development of our precompensation method, as well as the experimental design and statistical findings from tests carried out in order to assess the performance of the precompensation algorithms in their capability to enhance the access to GUIs for users that have refractive visual aberrations in the optical systems of their eyes.

## 1.1. Significance of this Research

According to the 1999 Census Bureau's Survey of Income and Program Participation (SIPP), there is an estimated 1.5 million visually impaired computer users. The number of people ages 15 and older with any "limitation in seeing", who report they have access to the Internet, is just over 1.5 million (1,549,000) [2]. 53% of individuals with general acuity loss report having access to the Internet, compared to only 28% of individuals with visual impairment extending beyond just general acuity loss [3]. Additionally, an estimated 7 million people in the United States alone have some type of high-order refractive aberration in their eye(s) [4]. In order to remain an active and functioning part of society, these individuals need to be able to interact in an efficient manner with graphical user interfaces [3]. Since the proposed method of precompensation is entirely implemented in software, this research seeks to benefit those individuals who suffer from high-order aberrations, allowing them to potentially interact with any type of digital display more effectively.

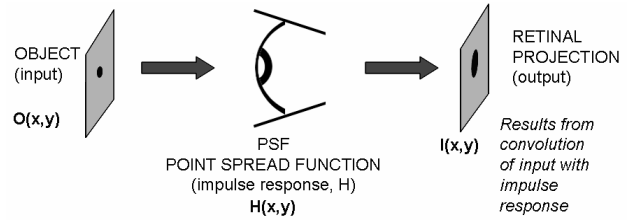
Additionally, this research exemplifies an exciting new direction towards the development of custom interfaces, which will be effectively matched to the specific capabilities of the intended user.

## 2. Precompensation Algorithm Overview

The human visual system can be thought of as a linear system having an impulse response  $H$  [5]. In a linear system, the output of the system is the convolution of the input with the impulse response of the system. The impulse response of an ideal optical system, including the human eye, is a delta function. Thus, if the user is free from any visual aberrations, the impulse response of his/her eye, from here on termed Point Spread Function (PSF), will be a delta function. This will result in a clear, undistorted projection of the computer image being viewed onto the user's retina, allowing the user to interact efficiently with the personal computer (PC) via the graphical display. If however, the user has a visual aberration, the PSF will not be a delta, and thus the retinal projection of the computer image will be distorted, hampering the efficient usage of the GUI [6].

Fig. 2 shows the Linear Shift Invariant (LSI) model used to describe the optical process that takes place when a user views an image (object). The image perceived by the user results from the convolution of an object, in this case an image on a graphical display, with the PSF of the user. Under ideal conditions, the

perceived image on the retina will be an undistorted version of the object. If the user has any type of visual aberration, the resulting image that falls on the retina will be a distorted version of the object.



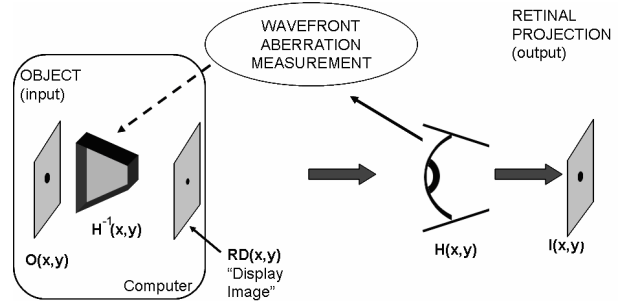
**Figure 2. Human Visual System Model**

Fig. 3 shows a block diagram of the proposed software precompensation system. The display image  $RD(x,y)$  is the result of deconvolving the user's PSF from an object image,  $O(x,y)$ . When viewed through the PSF, the eye's distortion is countered by the modification applied to the onscreen image in advance. The result is a clearer projection of the object image on the user's retina. This process is accomplished by indirect implementation of the following equations, through Wiener Filtering, as detailed in [1].

$$RD(x, y) = H^{-1}(x, y) * O(x, y) \quad (1)$$

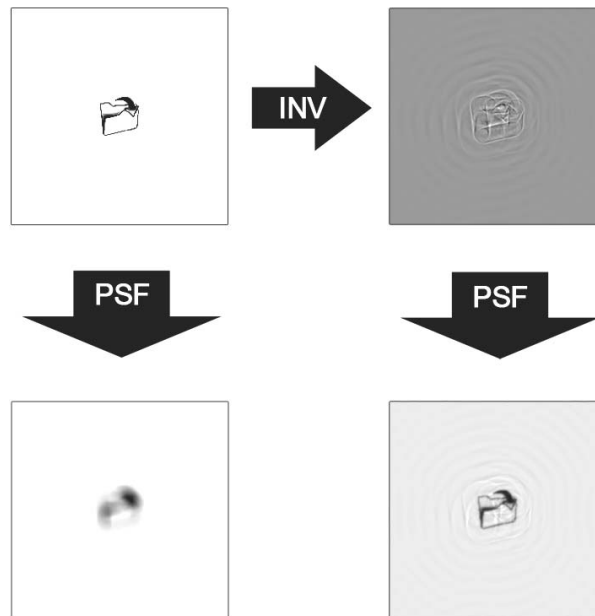
$$I(x, y) = H(x, y) * RD(x, y) = H * H^{-1} * O(x, y) \approx O(x, y) \quad (2)$$

where  $*$  denotes convolution,  $RD(x,y)$ , is the precompensated display image,  $H^{-1}(x,y)$  is the inverse PSF,  $O(x,y)$  is the intended object image, and  $I(x,y)$  is the retinal projection of  $O$ .



**Figure 3. Software precompensation process**

Figure 4 shows a schematic depiction of how the precompensation process is expected to enhance the visualization of an icon by a user with a typical defocus aberration.



**Figure 4. Simulation of ideal precompensation process: Icon with blur simulated (bottom left) Precompensated Icon with blur simulated (bottom right) (Grayscale in images scaled for display)**

The original, uncompensated icon (top-left) would be blurred by the PSF in the user's eye when viewed directly (bottom-left). However, if the inverse (INV) transformation is applied first to the icon as a form of precompensation, a modified display image (top-right) can be displayed to the user. When the user views the precompensated image (top-right), through the PSF that exists intrinsically in his/her eye, the sequential applications of the inverse (INV) and forward (PSF) transformations will tend to cancel each other, yielding a better perception of the icon (bottom-right).

### 3. Verification of the precompensation process

In order to gauge how much the precompensation process may facilitate computer interaction for the target population, several experiments were designed to measure the improvement in object recognition for objects displayed in a Windows™ desktop to human subjects that had varying degrees of visual refractive dysfunction.

#### 3.1. Human Subject Recruitment

Twenty subjects participated in the tests. Five of them were controls, i.e. they did not have significant

visual refractive errors. The remaining fifteen subjects were chosen as follows: Five subjects were chosen having only myopia, with at least -3 Diopters of sphere, five subjects were chosen having both myopia and astigmatism, with at least -3 Diopters of sphere and having astigmatism stronger than -0.5 Diopters, and five subjects were chosen to have been diagnosed with Keratoconus (an abnormal, usually asymmetrical shaping of the cornea) in at least one eye. Subjects participated in the evaluation without using any form of vision correction (glasses or contact lenses).

#### 3.2. Experimental Protocol and Design

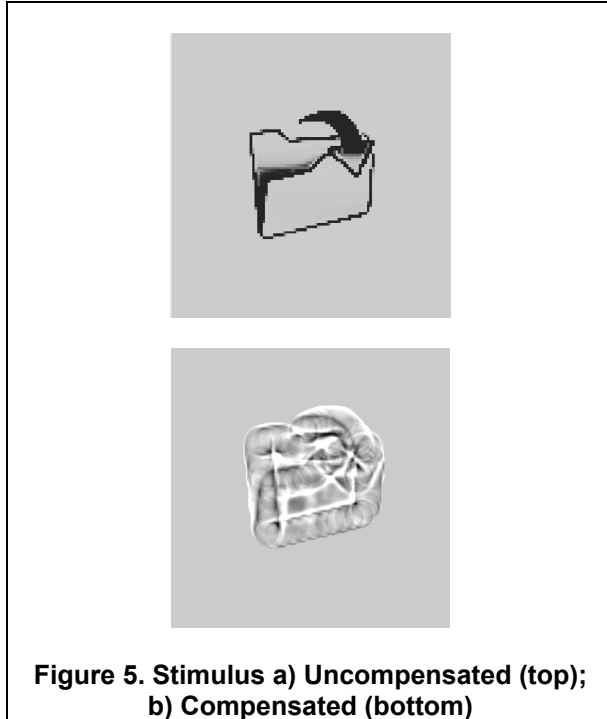
Each subject was positioned approximately 50 cm from a 21-inch, flat panel LCD screen, at a resolution of 1600 x 1200 pixels. Tests were performed monocularly. The test began by presenting the subject with a stimulus screen consisting of a large icon, with the maximum size being approximately 59 mm wide, uncompensated (e.g. Fig. 5-a). The initial stimulus icon was selected at random from a pool of six different Microsoft Windows icons (save, print, briefcase, binoculars, folder, and image).

The subject was then asked to indicate when he/she was ready for the target icons to be displayed. When indicated, all six target icons were displayed in a 2x3 array (Figure 6). The position and size of each icon was selected at random for each treatment level. The

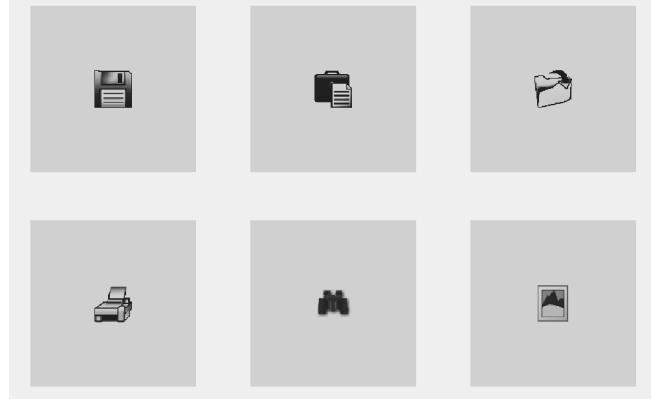
size of each icon could be 15 mm, 24mm, or 38 mm wide. The subject was then asked to point to the icon that matched the large stimulus icon previously shown. The answer for each target screen was recorded as a “correct” or “incorrect” identification of the icon.

Each icon position and size combination was tested twice. This amounts to thirty six trials for this test, i.e., uncompensated icons. The test was then repeated using precompensated stimuli (e.g., Fig. 5-b) and precompensated target icons. Once the uncompensated and precompensated tests were completed, the remaining eye was tested. The order of eyes tested was right eye first, then left eye.

Thus, the experiment can be considered a repeated measures experiment with four fixed factors: Group (G) – four levels, Eye (E) – two levels, Size (S) – three levels, and Method (M) – two levels (i.e., M=1 is without precompensation applied and M=2 is with precompensation applied). Every treatment combination was applied to the twenty subjects in a randomized order. The dependent variable is the number of correct icons per size, for each treatment combination, Y.



**Figure 5. Stimulus a) Uncompensated (top); b) Compensated (bottom)**



**Figure 6. Target Screen for the Icon Test (Uncompensated)**

The experiment is treated as randomized complete block design (RCBD) experiment [7], taking subjects as a random factor and blocking on it. The model for the analysis of variance is as follows:

$$Y_{ijkm} = \mu + G_i + P_{n(i)} + E_j + GE_{ij} + S_k + GS_{ik} + ES_{jk} + GES_{ijk} + M_m + GM_{im} + EM_{jm} + GEM_{ijm} + SM_{km} + GSM_{ikm} + ESM_{jkm} + GESM_{ijkm} + \epsilon_{ijkm} \quad (3)$$

with subjects nested in groups. The factors are summarized in Table 1.

**Table 1. Factors for human subject experiment**

Fixed Factors	Variable	Range
Group	$G_i$	$i=1:4$
Eye	$E_j$	$j=1:2$
Size	$S_k$	$k=1:3$
Method	$M_m$	$m=1:2$
Random Factor		
Subject	$P_n$	$n=1:20$

## 4. Results

### 4.1. Data Analysis

A nested factorial mixed ANOVA was used to analyze the experimental data. The data satisfied the assumptions (after transformation) required for parametric analysis, based on testing the Studentized residuals for outliers, normality, and testing the homogeneity of variance between cells [7]. Table 2 summarizes the ANOVA results for the human subject experiment.

**Table 2. – ANOVA results for Human Subjects Test**

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	16.395	137.018	.000
Group	3	16.395	2.717	.078
Size	2	97.645	6.567	.002
Eye	1	114.696	.470	.494
Method	1	114.696	48.450	.000
Group * Size	6	97.645	2.536	.025
Group * Eye	3	114.696	1.929	.129
Group * Method	3	114.696	10.024	.000
Size * Eye	2	97.645	3.835	.025
Size * Method	2	97.645	5.744	.004
Eye * Method	1	114.696	.184	.669
Group * Size * Eye	6	97.645	1.594	.157
Group * Size * Method	6	97.645	1.010	.423
Group * Eye * Method	3	114.696	.192	.902
Size * Eye * Method	2	97.645	1.047	.355
Group * Size * Eye * Method	6	97.645	2.054	.066

## 4.2. Key Findings

The main effects of Size and Method were found to be significant, with  $p < 0.002$  and  $p < 0.001$ , respectively. The Group\*Size, Group\*Method, Size\*Eye, and Size\*Method interactions were found to be significant at the 5% significance level ( $p=0.025$ ,  $p=0.000$ ,  $p=0.025$ , and  $p=0.004$ , respectively). This indicates that the method does improve the identification of icons for human subjects with the aberrations studied, and reveals that the method may work better for certain icon sizes.

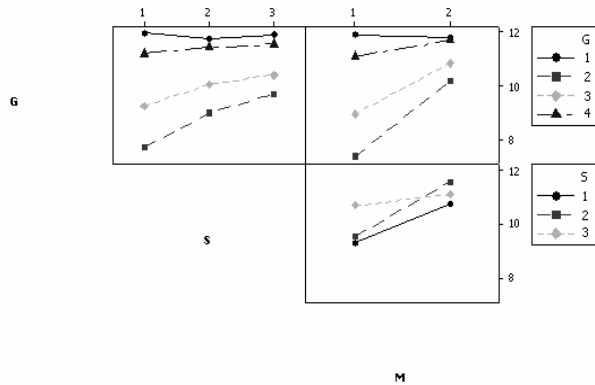
## 5. Discussion

The results of the experiments that were performed to assess the effectiveness of the proposed algorithm in precompensation of images for display on an LCD panel have shown that, for the subjects in the experiment, the precompensation method improved the identification of icons in a significant way by increasing the number of icons identified per trial from 9.825 to 11.15 ( $p<0.005$ ).

Ultimately, the proposed precompensation method aims to facilitate the usage of GUI environments by individuals with intractable visual dysfunction. The purpose of this test was to evaluate the usefulness of the proposed algorithm in improving the identification of icons displayed on-screen. The significance of the main effects of Size and Method confirms that the precompensation algorithm improves the ability of the subjects tested to identify the GUI elements used. Additionally, it was observed that the number of icons correctly identified goes up as the size of the icons increases. This is expected, as the larger the object, the easier it is to identify it.

Analysis of the significant interactions in the experiment reveals some interesting findings. For the group\*size interaction, the interaction plot (Fig. 7) shows that for group one, the control group, there was equal performance across all icon sizes. This is as expected, since the control subjects were chosen to have no significant visual aberrations. For group four, the keratocones, there is a slight increase in the number of identified icons as the size increases, although it is not large. This is primarily due to the fact that although the subjects from group four have Keratoconus, their prescriptions (except for the last subject in this group) are similar to the controls category (i.e. their spherical distortion is less severe than -2 Diopters). In other words, for purposes of viewing the computer screen, most of the keratoconic subjects performed nearly as well as the controls, with the exception of one subject. For groups two and three, the myopes and myopic-astigmats, the change is apparent. As icons increase in size, the number of icons identified also increases. This suggests that the severity of the aberration greatly affects the number of icons that a subject could identify. Keratoconus is a high-order aberration, whereas myopia and astigmatism (alone or combined) are second-order aberrations.

The group\*method interaction reveals similar findings. For the control group, the method does not improve the number of icons identified. This is expected because the control group should not need any precompensation to correctly identify the icons. The keratoconic group, as mentioned above, behaves similar to the control group, in that the number of icons identified is not greatly affected by whether or not they are viewing normal or precompensated icons. For groups two and three (myopic and myopic-astigmatic), the method was successful in improving the identification of icons by approximately three icons for group two and two icons for group three. This indicates that not all aberrations influence vision equally. This result matches similar independent observations found in the literature [8]. The last interaction, size\*method, reveals that for the largest size icon, the precompensation algorithm does not improve the identification of icons. This is as expected because for large icons, the original acuity requirement implicit in the identification task is less stringent and may be met by most subjects in these groups, even without precompensation. For the smaller icon sizes, i.e. sizes one (15mm) and two (24mm), the method does improve the identification.



**Figure 7. Group\*Size, Group\*Method, Size\*Method interaction plot matrix**

## 6. Conclusions

This paper presented the evaluation of a method to provide custom precompensation of visual aberrations for computer images with the following three key features:

1. Provides parameter-less operation, requires only the knowledge of the PSF of the user. (The PSF for a human eye can be derived from its wavefront aberration function, which is measured utilizing a wavefront analyzer)
2. Provides a significant increase in the ability for users to identify icons that were precompensated on a custom basis
3. Can be implemented on any PC capable of displaying RGB images on an LCD panel

These features have the potential to facilitate computer access for users with visual aberrations that cannot otherwise be assisted by conventional means (such as glasses or contact lenses). Results from the experimental evaluation indicate that the pre-processing algorithm provides compensation for human subjects by significantly improving their ability to identify icons displayed on an LCD panel.

In addition to addressing the specific needs of users with significant refractory dysfunction (e.g., Keratoconus), the method proposed and its verification provide important encouragement towards the continuation of efforts to develop adaptable, customizable human-computer interfaces in which the computer will read in the specific information of a given user and will re-configure its interface elements to match the specific capabilities of the user.

## 7. Acknowledgments

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