DISPLA 1408
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No. of Pages 14, Model 5+

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Displays xxx (2007) xxx–xxx

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# ClearType sub-pixel text rendering: Preference, legibility and reading performance

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**Abstract**

ClearType is an onscreen text rendering technology in which the red, green, and blue sub-pixels are separately addressed to increase text legibility. However, it results in colored borders on characters that can be bothersome. This paper describes five experiments measuring subject preference, text legibility, reading performance, and discomfort symptoms for five implementation levels of ClearType rendered text. The results show that, while ClearType rendering does not improve text legibility, reading speed or comfort compared to perceptually-tuned grayscale rendering, subjects prefer text with moderate ClearType rendering to text with grayscale or higher-level ClearType contrast. Reasons for subject preference and for lack of performance improvement are discussed.


*Keywords:* Sub-pixel rendering; Font; Legibility; Readability; Reading; Resolution; ClearType



## 1. Introduction

Computers and digital devices dominate the office, amusement and entertainment businesses. Even though text can be easily viewed on electronic displays, people often prefer to print documents and read the hard copy. One possible reason for the preference of printed pages to onscreen text is the compromised image quality of electronic displays, which have limited addressable pixels compared to very high number of addressable points for printed images. For example, to present a 10-pt font character on a typical computer screen of 96 dpi (actually should be *pixels per inch, or ppi*), only 13.33 ($=10 \times 1/72 \times 96$) pixels are available in the vertical dimension to represent all vertical designing features of the same font type family including capital letters, letters with ascenders and descenders, and space for side bearings. While most current computer displays have resolutions of 72–130 ppi, a typical laser printer offers resolution of 300–1200 dpi (dots per inch). The limited pixel matrix on computer displays poses serious challenges in designing screen fonts. Viewed with magnification, the same-sized character appears smooth and sharp on paper but blocky and jagged (or "aliased") on the computer screen. The image quality becomes worse with smaller font sizes and lower resolution displays with resulting loss of fine details and reduced legibility, and appears jagged with larger font sizes [1] (see Fig. 1: aliased text).

### 1.1. Grayscale rendering

Grayscale is a common-used anti-aliasing technique used to smooth the edges of aliased text. It works by assigning gradient shades of gray to the pixels of a character according to the percentage that the pixel is involved in the idealized image. For black text on white background, rather than a choice of "on or off", each pixel is usually stored as a byte with value between 0 and 255 to indicate the level of gray. It has been shown that a thin impercepti-

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doi:10.1016/j.displa.2007.09.016

| Aliased | Grayscale | ClearType (contrast = 1.0) |
|---|---|---|
| This is text in 6-pt TNR. | This is text in 6-pt TNR. | This is text in 6-pt TNR. |
| This is text in 8-pt TNR. | This is text in 8-pt TNR. | This is text in 8-pt TNR. |
| This is text in 10-pt TNR. | This is text in 10-pt TNR. | This is text in 10-pt TNR. |
| This is text in 12-pt TNR. | This is text in 12-pt TNR. | This is text in 12-pt TNR. |
| This is text in 14-pt TNR. | This is text in 14-pt TNR. | This is text in 14-pt TNR. |

Fig. 1. The effect of font rendering technique by font sizes. The sentences were created in MS Word, displayed in Times New Roman at different font sizes. A screen shot was taken (by PrintScreen) each time the font smoothing setting was changed in ClearType Tuner. The derived image was copied and pasted onto MS Paint to save as a bmp file.

ble gray strip interposed between a black/white border causes a perceived displacement of the border [2]. This result provides the basis by which gray pixels can help to create smoother edges to the perceived image. Studies have shown that, compared to aliased text, grayscale enhances reading performance in character identification [3] and decreases visual discomfort [3]. Grayscale also has been shown to decrease search time at letter search tasks and subjects report preference for grayscale text to aliased (b/w) text [4]. Although grayscale rendering is an improvement over aliased text, it is not good enough for comfortable reading on screen for extended hours, as most office workers do today. In addition, at smaller font sizes, the text becomes extra blurry and hard to read [1,5] (see Fig. 1, grayscale text). The problem with grayscale is that the smoothing technique is at the whole-pixel scale. Constrained by the limited number of screen pixels available for a character, the text image tend to be blurred with foggy edges and hard to focus at, which is fatiguing for eyes.

### *1.2. Sub-pixel rendering*

The latest anti-aliasing technique is *sub-pixel rendering*, used to increases screen resolution in liquid crystal displays (LCDs) by separately addressing sub-pixels [5–8]. In LCDs each pixel is comprised of three primary sub-pixels (red, green and blue) arrayed as vertical bars in a fixed order of RGB or BGR. Normally the relative luminance of the 3 sub-pixels is spatially summated by the visual system to determine the perceived brightness and color of the whole pixel as in Cathode Ray Tubes (CRT) displays. Different from CRT, in which a "pixel" is a projected dot generated by beaming electrons on phosphor screen with color "bleeding" onto neighboring pixels to create the effect of edge-smoothing, LCD pixels are on real pixel grid with sharp edges to define each pixel boundary, which loses the side-effect of color bleeding [9]. However, the rigid sub-pixel layout allows LCD to address each of the sub-pixels separately as an independent unit and precisely with the designated amount of colors. By carefully controlling the luminance of the red, green, and blue sub-pixels to highlight the body of the character, it increases screen resolution to 300% horizontally; hence it can be called a "color anti-aliasing" technique. A consequence of sub-pixel rendering, however, is that the characters have colored sub-pixels on their edges which can cause some unwanted color perception. The challenge in sub-pixel rendering is to maximize the increased resolution while minimizing the color artifacts, by employing the knowledge of human visual system [5–7,10–12].

There are several characteristics of human visual system affecting what we perceive from a computer display. First, our visual system is more sensitive to changes in luminance than to changes in hue or saturation; in other words, we are more capable in detecting the change of luminance (or perception of different sheds of brightness) than the change in color. Second, the perceived luminance (i.e., *brightness*) depends on surrounding luminance. Therefore the same shed of gray can look different with different background luminance while different sheds of gray can be perceived identical with different surroundings. Third, human vision is more sensitive to luminance contrast than absolute luminance. Therefore, minor tune in luminance may cause significant difference on brightness depending on its contrast to the surroundings. Fourth, human visual system tends to undershoot or overshoot around the boundary of regions of different intensities. The imbalance of human vision to luminance and color allows display technology to create an illusion of font smoothing at the pixel level by manipulating color depth of sub-pixels, and the key is in tuning the color to the right brightness but lowering the chromatic scheme to below the threshold of just noticeable difference (jnd).

### *1.3. ClearType technology*

ClearType is an example of the sub-pixel rendering, developed by Microsoft and tested in this study. It starts with a full-color image, over-samples the horizontal dimension to at least 6 times, and then pre-filters each sub-pixel color channel with a low-pass filter to remove small details. The trick in ClearType is how it removes the color anomaly at the edge of the glyph. For instance, for a dark character on a light background, a stroke with 5 sub-pixel width (e.g., GBRGB) will have two sub-pixels (G and B) off and one sub-pixel (R) on in the first triplet, which leads to a colorful edge (in this case, redness on the left side of the stroke). ClearType takes the advantage of human sensitivity to luminance over color and turns the problem to local luminance inconsistency rather than dealing with the color fringe directly [5,18]. Using the *BOX filter RGB decimation* [16], the pre-filtered image undergoes a special displaced sampling process. The sub-pixel samples are taken by displacing the same color filter onto a whole-pixel-wide box centered at the sub-pixel with correspondent color. The luminance of each sampled sub-pixel (e.g., R) is determined by the luminance of itself and its two immediate adjacent neighbors (e.g., B on the left and G on the right) at equal weights (i.e., 1/3 each). In other words, the luminance of each sub-pixel is evenly spread into its two immediate adjacent neighbors to rebalance local discoloration. However, the process of box filter (i.e., equal luminance sharing) creates wider edges that could blur the image as in grayscale. ClearType resolves this problem by repeating the box filter decimation process again so the luminance energy in the original sub-pixel is now spread into its 4 neighbors, with energy stepped down from the centered sub-pixel itself (1/9, 2/9, 3/9, 2/9, 1/9). With multiple box-filtering, a clear image is created with clear contrast for the body of the character at the cost of small color errors on the edges, which are less visible from normal viewing distances. The process of RGB decimation eliminates phase error that is encountered in whole-pixel grayscale anti-aliasing due to the inconsistent timing of different light components [16]. The final output of the box filter decimation process is further improved through additional techniques, such as display-specific hinting and/or kerning, to refine the text image to look sharp and clear on screen. (See Fig. 1, "ClearType text"; further details see references [5,10,12].)

Sub-pixel rendering needs accurately put designed amount of luminance to individual sub-pixels, hence it only applies to displays with individually addressable sub-pixels, not to CRTs or analog input LCDs. Also, the result of these filtering techniques is sensitive to the brightness of the display; without proper tuning the display signal intensity, the image may look bleached out or too dark and the color edge may look intruding. To prevent this problem, the input signal to the display must be "gamma corrected" before implementing ClearType or other sub-pixel rendering techniques, that is, adjust the intensity of the output image (the perceived brightness) to the proper amount to reflect the strength of a display's input signal (the voltage). Other factors that affect the image quality include the ambient lighting, the configuration of the computer systems, and individual's color sensitivity. The computer configuration includes the software to present the text (e.g., MS Word or Netscape), the installed graphic cards, to the standard hardware on the motherboard. Individual's subjective perception also affects the perceived text quality. Human color vision is achieved by the sensitivity of the cone cells to hue differences of the opponent curves, which is variable across individuals. As mentioned above, the key of sub-pixel rendering is to tune the color brightness while control the chromatic scheme to below the jnd, a threshold varied based on individual color sensitivity. Therefore the final product of a simple character image with sub-pixel rendering can be view differently from individual to individual.

Since the color schemes of the computer system and display device differ from one to another, along with the variation of individual user's color sensitivity, Microsoft offers *ClearType Tuner PowerToy* (free download from http://www.microsoft.com/typography/ClearTypePowerToy.mspx) for user to adjust the gamma level and tune to the ClearType level to best fit individual preference, and the setting will apply to the whole system. ClearType rendered text can also be obtained through Microsoft Reader (MS Reader), which is defaulted for reading within MS Reader, but can also be saved as a text image file through screen copy. MS Reader offers five levels of sub-pixel rendering, with level 0 shows no color filtering (i.e., grayscale), and level 1 to 4 showing color contrast from low to high. As mentioned above, ClearType uses the box filter RGB decimation process to improve image contrast and control color fringe. By changing the weights of the centered sub-pixel and its neighbors, it produces different levels of contrast and discoloration in the character. The higher the weight at the centered sub-pixel (e.g., level 4), the less the luminance-sharing with neighboring subpixels, resulting in a sharper image and more serious color anomaly. Fig. 2 presents enlarged looks of a 14-pt Times New Roman letter b generated in MS Word through ClearType Tuner and in MS Reader at different contrast levels, in comparison to aliased (black & white) and grayscale text. Although all images were generated in the same system, the images generated from MS Word (the second row) are different from that of MS Reader (the third row), showing the effect of the software.

In the current study, the text stimuli were generated in MS Reader, showing the 5 levels of ClearType contrast, with level 0 as the *control condition* indicating no ClearType color filtering but grayscale text presentation, level 1 as *lowest-contrast text*, level 2 *lower-contrast text*, level 3 *higher-contrast text*, and level 4 *highest-contrast text*. Different from regular grayscale text, the grayscale text generated in MS Reader applies ClearType technology except the 3 sub-pixels are tuned the same to give gray-scale colors. It also retains the advantage of ClearType hinting and kerning, which may improve the text image better than regular grayscale text, though empirical test is needed for this statement.

### 1.4. Previous studies of ClearType effect

Despite the new debut of ClearType, a limited number of studies have reported the effect of ClearType on text quality and reading efficiency. In a series of studies [13–16], Gugerty, Tyrrell and colleagues let subjects tune the ClearType contrast for their own preference. They found that ClearType was rated as more readable, creating less

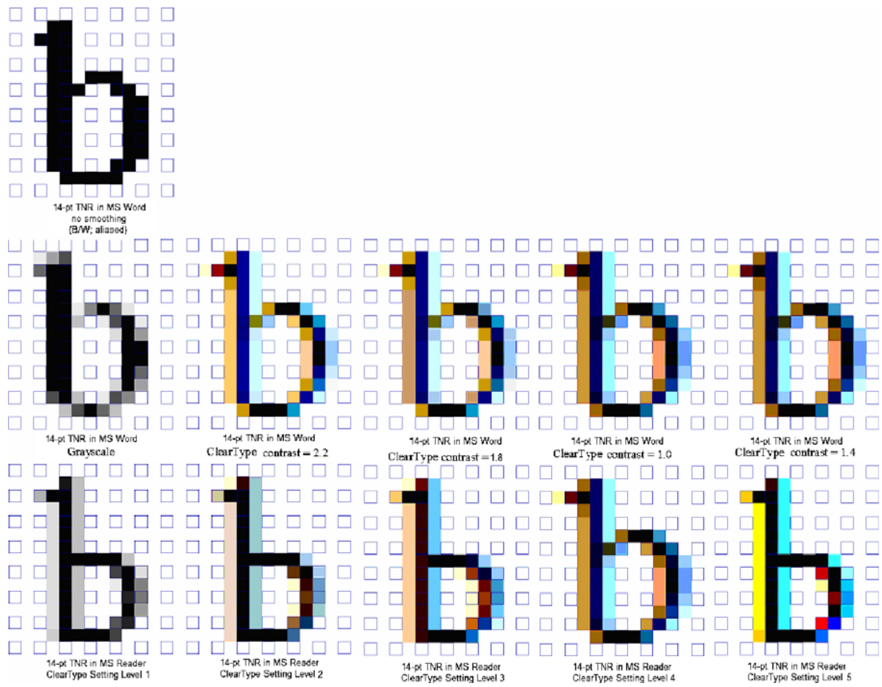


Fig. 2. Enlarged look of the font rendering effect. The figure shows how the image of letter b in 14-point Time New Roman changed with different font rendering mode and ClearType levels, An image of letter b in Times New Roman was first created in MS Word. Each time after a change of the ClearType setting in ClearType Tuner, the image was looked through an onscreen magnifier to 36×, a screenshot of the enlarged image was taken, pasted onto MS Paint, and then saved as a bmp file to show the chromatic scheme under different font rendering at the pixel level.

mental fatigue, and was clearly preferred over the aliased display. However, there have been inconsistent findings on task efficiency. In their first study [13] no significant differences in subject's speed in novel reading and their eye movements during reading. In later experiments, ClearType improved accuracy over aliased text in a lexical decision task in which subjects were asked to judge whether a briefly presented letter string is a word [14], enhanced response speed in sentence comprehension but did not affect its accuracy [15], and showed improvement at both response accuracy and speed over anti-aliased (grayscale) text in a tachistoscopic word-naming task and over aliased (black & white) text in a sentence comprehension task [16]. Dillon et al. also observed improvement in reading speed with ClearType rendered text over aliased text in 12-pt Arial font [17,18], some advantage in text scanning [18], but no difference on performance accuracy, preference or visual fatigue scores [17,18]. The incongruent data reveals substantial differences on the advantage of using ClearType, which may differ with task requirement and/or individual preference to ClearType contrast. In addition, most of the above studies compared ClearType anti-aliasing with aliased text (except [15]). It is not clear whether the ClearType advantage remained when compared with standard smoothed (i.e., grayscale) text.

Ever since the introduction of ClearType, there have been different opinions toward it (e.g., discussion in MSDN Blogs, http://blogs.msdn.com/fontblog/). Our objective in the series of experiments reported herein was to investigate the effect of various stepped ClearType contrast levels, in comparison to grayscale text, upon threshold text legibility (Experiment 1), subjective preference (Experiment 2), and reading speed and visual discomfort symptoms (Experiment 5). We also studied whether individual preference of ClearType contrast level relates to the individual's color discrimination and detail perception (i.e., visual acuity) (Experiment 3) and whether preference and perceived color disturbance was different in the central and peripheral visual fields (Experiment 4).

## 2. General methods

Thirty subjects (ages 18–38 yrs) participated in all 5 experiments. Subjects were screened to meet the following criteria: visual acuity (corrected or uncorrected) of 20/20 or better in each eye, normal color vision, and no ocular pathology. All subjects consented to participate according to protocol approved by the Ohio State University Institutional Review Board and received $10/h for their participation.

The reading text was displayed in 10- or 12-pt Verdana fonts, generated in MS Reader with 5 levels of ClearType color filtering as described above (see Fig. 3 for exemplars). Verdana is a sans serif font developed by Microsoft specifically for onscreen display. It was selected as the test font because it has been shown to have higher legibility than other commonly used fonts [1]. All presentations were operated by a computer with Windows XP operating system and displayed on a Sony SDM-M61 16-in. LCD mon-

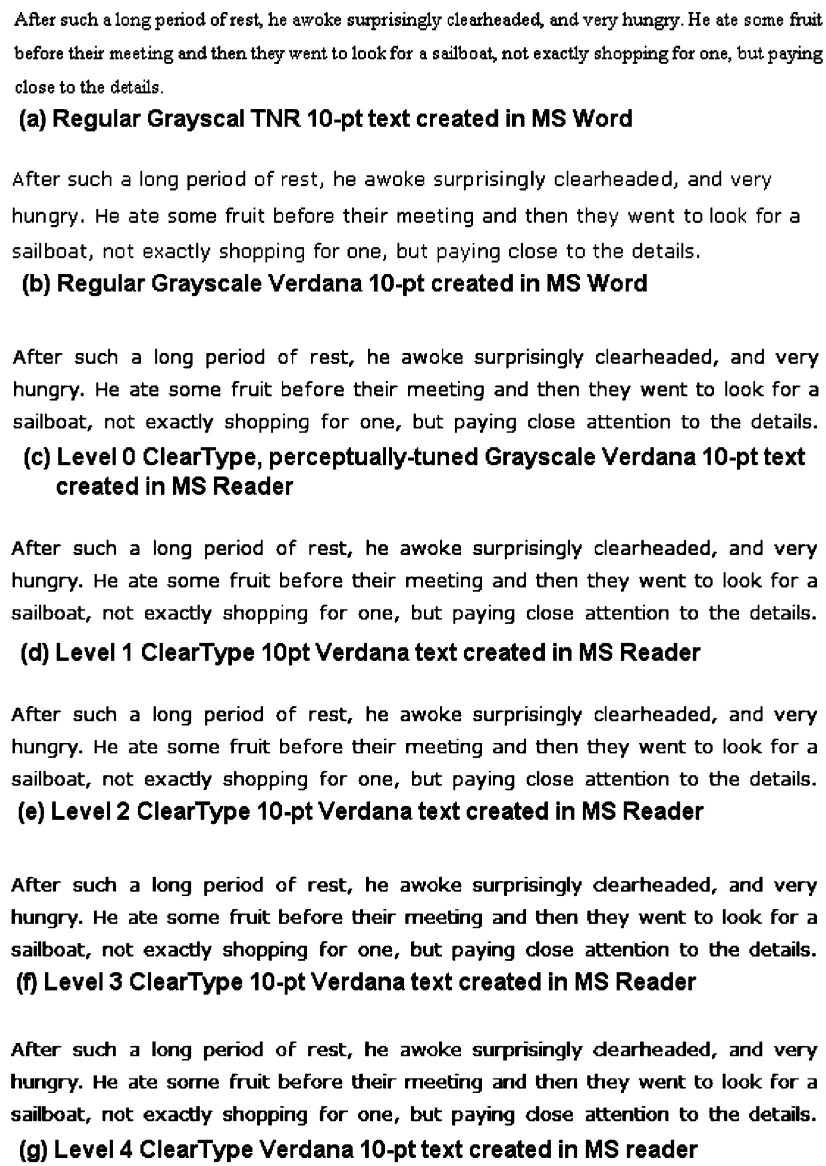


Fig. 3. Examples of text rendered with different levels of ClearType contrast, created in MS Reader, in comparison with text created in MS Word with different font types.

itor at native resolution (1280 × 1024 pixels, 96 dpi, 32 bits color quality, refresh rate of 75 Hz).

## 3. Experiment 1: threshold legibility

### *3.1. Methods*

Experiment 1 compared the threshold legibility of 10-pt Verdana letters and words at the 5 levels of ClearType contrast. Legibility was measured with a step-backward distance visual acuity method. This method was derived from the clinical method of measuring visual acuity as a standardized procedures for comparing legibility of text on visual acuity charts [19–21]. Characters on clinical visual acuity charts are designed with a 1:5 stroke width to character height ratio. The stroke width is considered the minimum angle of resolution (MAR) and subtends 1 min of arc for 20/20 vision. Therefore a 20/20 character subtends 5 min of arc in height and a 20/40 character subtends 10 min of arc degree, etc. For clinical visual acuity measure, the patient stands at a fixed distance whereas the size of the characters decreases for each subsequent lower line on the chart. However, this approach is not plausible for testing onscreen stimuli because of the aliasing effect of the pixels which particularly affects the integrity of small-size characters. Therefore, for legibility testing the major deviation from typical clinic measurement is that, rather than decreasing the size of the characters to create smaller acuity levels, the same sized characters are used for each acuity row but the subject is asked to step back to a prescribed longer viewing distance to decrease the angular size from one row to the next. This variation in technique is important because it maintains the character integrity throughout the acuity testing range with the same pixel configuration of the computer screen. Otherwise, visual acuity was measured according to standardized methods. Conventionally visual acuity measurement is specified in terms of logMAR (the log value of MAR). Therefore, at 20/20 visual acuity (MAR = 1 min of arc), logMAR is equal to 0 (log (1) = 0). Smaller logMAR values represent smaller visual angle, herein better legibility.

Visual acuity at each ClearType level was measured separately with letters and words in an order determined by a Latin square design. Each acuity row on a letter chart contained 5 stimuli (letters or words). For letter charts, 2 out of the 5 letters had either an ascender or a descender and the remaining 3 letters with neither. For word charts, all of the 5 words had 5 or 6 letters with at least one ascender/descender. The proportions of high- and low-frequency words on a word chart were equally distributed for every presentation. Only one row of 5 letters or words was displayed at a time and viewed from an assigned distance. Subjects were asked to read the 5 stimuli on a computer display from an assigned distance. Viewing distances began at the 20/40 visual acuity line, a viewing distance at which the subject could identify all 5 letters or words, and were increased in 0.1 logMAR steps (i.e., viewing distance moved from 20/40, 20/32, 20/25, 20/20, 20/16, to 20/12.5, and the logMAR decreased from 0.3, 0.2, 0.1, 0, −0.1, −0.2, to −0.3 correspondingly). Subjects were encouraged to guess and testing proceeded to further testing distances until no characters in a row could be identified. With each step of increased viewing distance represented −0.1 logMAR, each letter or word properly that was identified in a row added −0.02 logMAR units to the final acuity score for that chart. The logMAR values were then transformed to relative legibility (1/MAR) for each subject at each testing condition (letter/word chart at each ClearType level), with larger value indicating better relative legibility. The relative legibility for each tested condition was calculated by averaging across all subjects. The derived data were analyzed with repeated measures ANOVA (alpha error = 0.05). For the current and the following analyses using Repeated ANOVA, the Greenhouse-Geisser df-adjusted test will be used if the sphericity assumption was violated.

### 3.2. Results

The average letter and word legibility for each ClearType level are shown in Fig. 4. Consistent with the results of a previous study [1], letter legibility was approximately 20% greater than word legibility, indicating that words need to be increased in size by about 20% to be equally legible with individual characters. However, no significant difference was observed compared to grayscale text (Level 0, the controlled), or between different ClearType contrast levels, for either words or letters.

While both studies required subjects to name the displayed stimuli, our findings are different from Gugerty et al.'s [16],in which ClearType was found to significantly improve the accuracy and speed of word naming (compared to grayscale text, but not to aliased text) in a tachistoscopic word naming task. However, there have been several differences in study design between the two studies. (1) While both studies used 10-pt Verdana font for text naming, Gugerty et al. measured word naming accuracy and speed at suprathreshold size (i.e., text was always considerably larger than threshold), but the current study measured the threshold for text recognition with ample showing time (i.e., find the smallest visual angle of text that can be identified with ample viewing time). It is possible that ClearType may improve performance at supra-thresh-

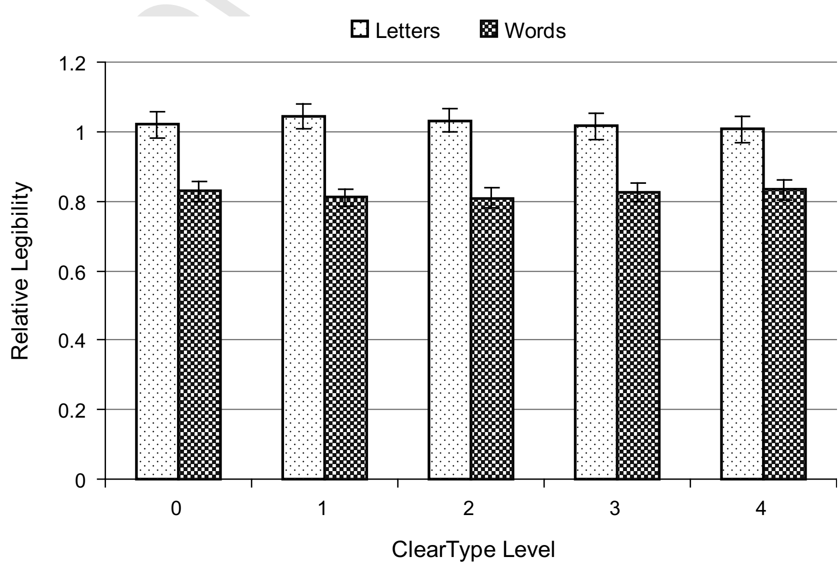


Fig. 4. Mean relative legibility for each ClearType level.

old sizes but not at threshold detection, or only under time pressure. How does the threshold measure relate to supra-threshold performance is an issue that is still under investigation [22]. (2) While both studies used grayscale anti-aliasing as control, the resulted grayscale text quality may be different. In Gugerty et al., a special version of 10-pt grayscale Verdana text was used, but in the current study the grayscale text was created in MS Reader, the same way we used to create other levels of ClearType. MS Reader text is usually better hinted, with even letter spacing, hence is generally better looking and more readable (see Fig. 3(c), in comparison to (a) and (b)). With all text created in MS Reader, it kept other factors the same and limited comparison more direct to font rendering methods. It is not clear whether the observed ClearType advantage related to other factors such as hinting or spacing adjustment (kerning), but it does point out the potential importance of other text qualities that are improved along with ClearType. (3) In Gugerty et al., subjects tuned the ClearType contrast to individual's preference, while the current study tested legibility at different ClearType contrast levels. The ClearType effect may be concealed by averaging subjects' score, if there is great individual difference on preference of ClearType contrast.

## 4. Experiment 2: preference for ClearType level

### 4.1. Methods

Experiment 2 examined user preference for ClearType contrast level. All combinations of the 5 ClearType contrast levels were presented to the subjects in pairwise fashion. For each presentation, the same paragraph of text was simultaneously displayed side-by-side with two selected ClearType levels. Testing was performed for both 10- and 12-pt Verdana font. Within each font size, each pairwise combination of ClearType levels was presented twice using Latin square ordering. Subjects used an analog to digital slider (100 mm long) to indicate their preference between the two paragraphs based upon which they would prefer to read. The scale was marked "strongly prefer" at each end and "moderately prefer" at the midpoint from center to end. Subjects were instructed to move the slider towards the paragraph with the ClearType level they preferred or to leave the slider in the center if no preference. After each presentation subjects also filled out a questionnaire on which they rated (on an analog scale of 0–100 mm) each of 3 independent reasons (color, clarity and contrast) why they judged one presentation to be less desirable than the other.

### 4.2. Results

#### 4.2.1. Preferred ClearType level

The rating of subjects' preference for each pairwise presentation was recorded as two scores, one for each ClearType level. For example, a rating at 60 mm from the left end was encoded as preference 60 for the ClearType level on the right-side text and 40 for the ClearType level on the left-side text. The mean preference ratings across all presentations for each ClearType level are shown in Fig. 5. Statistical comparisons were made with a one-sample $t$-test against the neutral value of 50, which represents no preference between the two displayed levels. The results show that subjects had statistically significant preference for ClearType levels 1 and 2 for 10-pt font (strongest preference for level 1) and for level 2 for 12-pt font. The preference ratings dropped significantly below 50 for ClearType levels 3 and 4 for 10-pt font and for level 4 for 12-pt font, indicating that those conditions were relatively disliked. These data show that lower levels of ClearType contrast are preferred and higher levels of ClearType



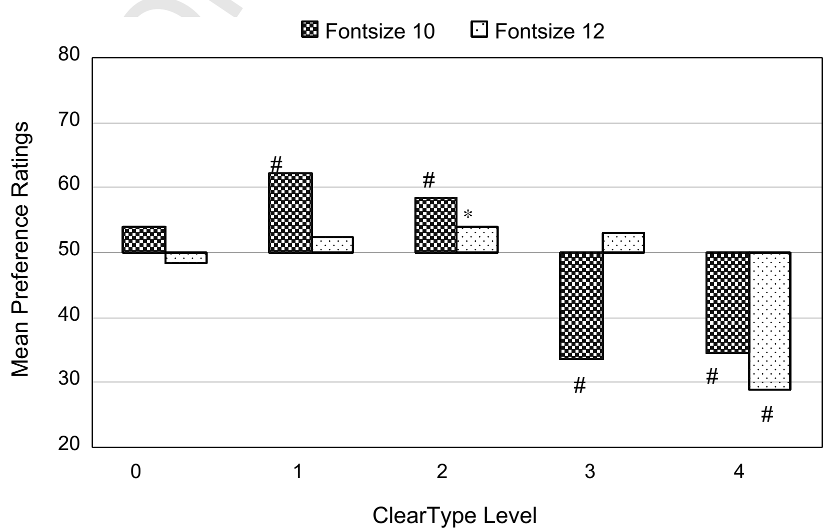


Fig. 5. Mean preference ratings for ClearType levels for both 10- and 12-point font. Values greater than 50 indicate preference and values less than 50 indicate non-preference for the correspondent ClearType level. Statistical differences from neutral value of 50 are indicated ($^{*}p < .05$; $^{\#}\ p < .0001$).

Please cite this article in press as: J. Sheedy et al., ClearType sub-pixel text rendering: Preference, ..., Displays (2007), doi:10.1016/j.displa.2007.09.016

contrast are less-liked: also, higher ClearType contrast was accepted for 12-pt font than for 10-pt font.

The data were further analyzed by comparing the mean preference settings for each pairwise presentation. For each pair, the preference value for the higher ClearType level was tested against the neutral-preference value of 50 to determine if the preference for the higher ClearType level was statistically significant (Table 1). Values less than 50 indicate preference for lower ClearType contrast and values greater than 50 indicate preference for higher ClearType contrast. For 10-pt font, level 1 was preferred over level 0 (grayscale, $p = 0.021$). Preference for level 2 was neutral compared to either level 1 or level 0. All three lower ClearType levels (0, 1, 2) were more preferred ($p < 0.0001$) over the two higher levels (3 and 4). No significant difference was found between level 3 and level 4. For 12-pt font, level 1 and 2 was slightly preferred over level 0 and 3 but the preference values were not significantly different from 50, indicating no difference in preference among those levels; however, each of them was significantly preferred over level 4, suggesting least preference for the highest ClearType contrast.

The results of both analyses are consistent. While the highest-level of ClearType contrast was clearly not preferred at both font sizes, a higher level ClearType contrast (up to level 3) was accepted for 12-pt font than for 10-pt font (up to level 2), which may be explained by the smaller ratio of sub-pixel to image size, consequently less relative amount of color fringe, for 12-pt font than for 10-pt font. Combined with results from Experiment 1, while there is individual difference over ClearType contrast level, subjects were clearly dislike highest level of ClearType contrast (level 4). If individual preference would mask the ClearType effect on text legibility, we should have seen clearly poor legibility at level 4 text. Since this prediction is not supported by the results, we maintain our statement that ClearType rendering has no effect on text legibility.

#### 4.2.2. Reasons for preference

For each pairwise presentation, subjects were asked to explain their response in terms of three factors (color, contrast, and clarity). The average ratings of each reason for dislike a certain level in each paired presentation are presented in Table 2.

It may be seen by inspection that the mean ratings for contrast and clarity at each of the pairwise presentation are similar to one another, which are very different from the ratings for color. Pairwise *t*-tests were used to compare

Table 1
Mean preference settings for higher ClearType levels compared to lower ClearType levels for 10-pt and 12-pt font

| Lower Level | 10-point Verdana | | | | 12-point Verdana | | | |
|---|---|---|---|---|---|---|---|---|
| ClearType | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Higher level ClearType | | | | | | | | |
| 0 | 59.0$^{*}$ | 53.0 | 27.9$^{**}$ | 32.5$^{**}$ | 52.3 | 55.0 | 49.0 | 32.0$^{**}$ |
| 1 | | 51.4 | 30.4$^{**}$ | 30.1$^{**}$ | | 52.1 | 48.2 | 31.2$^{**}$ |
| 2 | | | 29.8$^{**}$ | 33.2$^{**}$ | | | 47.7 | 29.7$^{**}$ |
| 3 | | | | 48.6 | | | | 33.2$^{**}$ |

Preference was scaled from 0 (indicating higher level is not preferred) to 100 (indicating higher level is preferred). Preferences that are significantly different from neutral (50) are indicated ($^{*}$ $p < 0.05$; $^{**}$ $p < 0.01$).

Table 2
Average rating (0–100) of color, contrast, and clarity as reason for not choosing a particular ClearType level

| Reason | Lower Level CT | Higher level ClearType contrast | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 10-point text | | | | 12-point text | | | |
| | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Color | 0 | 12.3 | 5.3 | 55.2 | 51.1 | 5.1 | 11.4 | 28.5 | 48 |
| | 1 | | 7.8 | 54.5 | 60.1 | | 9.7 | 26.4 | 52.1 |
| | 2 | | | 58.2 | 54 | | | 24.4 | 51 |
| | 3 | | | | 15.2 | | | | 43.5 |
| Contrast | 0 | 31.9$^{**}$ | 21.6$^{**}$ | 29.1$^{**}$ | 27.3$^{**}$ | 27.6$^{**}$ | 27.6$^{*}$ | 26.9 | 28.9$^{*}$ |
| | 1 | | 20.1 | 23.8$^{**}$ | 24.8$^{**}$ | | 14.3 | 21.9 | 25.7$^{**}$ |
| | 2 | | | 35.7$^{**}$ | 28.0$^{**}$ | | | 20.6 | 25.2$^{**}$ |
| | 3 | | | | 13 | | | | 24.0$^{*}$ |
| Clarity | 0 | 31.2$^{*}$ | 21.9$^{**}$ | 23.9$^{**}$ | 21.1$^{**}$ | 26.0$^{**}$ | 19.2 | 30.1 | 22.8$^{**}$ |
| | 1 | | 18.3 | 22.3$^{**}$ | 23.1$^{**}$ | | 18 | 24.4 | 23.3$^{**}$ |
| | 2 | | | 25.0$^{**}$ | 23.5$^{**}$ | | | 23.9 | 23.9$^{**}$ |
| | 3 | | | | 9.4 | | | | 22.4$^{*}$ |

Statistical testing compared the difference between color/contrast and color/clarity for each pair and significance is indicated ($^{*}$ $p < 0.05$; $^{**}$ $p < 0.01$) next to the contrast and clarity ratings respectively.



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the importance rating of contrast and clarity (each separately) to the color rating. For example, for pairwise presentation of level 0 and level 1, the value of 31.9 for contrast rating and the value of 31.2 for clarity rating were (individually) compared to the value of 12.3 for color rating. The results show that color was the primary reason for aversion to a higher-contrast ClearType display (e.g., levels 3, 4 vs. levels 0, 1, 2 for 10-pt font, and level 4 vs. levels 0, 1, 2, 3 for 12-pt font), and the weight increased significantly from lower to higher ClearType levels. In contrast, when a lower-contrast ClearType display (level 1 and 2) was not chosen when compared to a higher-contrast display, the main reason was because of (poor) clarity and contrast, not color. Together, these results show that higher-level ClearType was less preferred because of color anomaly, and lower ClearType levels were often preferred for less color fringe; and if they are not selected, it is because of the (poorer) clarity and contrast.

Overall, these results are consistent with the fact that ClearType is a technique used to improve image integrity (clarity and contrast) while battling with increased color artifact. In general, subjects preferred the lower-levels ClearType contrast, which improve text clarity better than standard anti-aliasing (grayscale) without getting excessive unwanted colors.

## 5. Experiment 3: individual visual characteristics vs. ClearType preference

The results of Experiment 2 indicate that lower ClearType contrast improves perceived contrast and clarity but higher ClearType contrast causes aversive perception of color anomaly. As discussed in the introduction, human eyes are very forgiving, we tend to tune out the middle-frequency light waves (e.g., greenish-yellow and reddish-purple lines) on light or dark edges; still, these unfocused colors tend to muddy the image color and reduce the visible details, and the effect varies from individual, probably due to individual's lens and/or cone cell sensitivities. If so, will individual preference of ClearType contrast differ by their vision? More directly, will people with better visual acuity prefer higher ClearType contrast as it improves image clarity better? Will people with better color discrimination prefer lower ClearType contrast as they are more likely to detect the color anomaly? In Experiment 3 we measured individual's visual acuity and color discrimination ability and tested whether they are related to individual preference for ClearType level measured in Experiment 2.

### 5.1. Methods

The primary dependent variable for this experiment was individual preference for ClearType level, based upon the preference data in Experiment 2. For each subject, the mean preference for higher ClearType contrast compared to lower ClearType contrast was determined separately for 10- and 12-pt fonts, with higher value indicating preference for higher ClearType contrast (hence better clarity). The means of each subject's ratings of color, contrast and clarity were also calculated separately for 10- and 12-pt fonts and used as dependent variables for preference reason. High values suggest more emphasis on the tested trait. Individual's visual acuity and color discrimination were measured as independent variables, using the following methods: Individual's visual acuity was represented by his own relative legibility score measured in Experiment 1, with higher relative legibility for better visual acuity. Their color discrimination ability was measured with the Farnsworth Munsell 100 Hue (FM100) color vision test (Richmond Products, Richmond, CA), which was performed binocularly under standard illumination (Illuminant C – 6740 K). The caps in the four cases were randomly arranged before each presentation and the subject arranged the caps according to color. After arrangement the sequence of the numbers was recorded. The total error score was calculated for each subject, with higher error scores for poorer color discrimination. If visual acuity affects individual's emphasis on image clarity, it is expected positive correlation between visual acuity and ClearType preference, contrast- and clarity-attribution (higher acuity → ask for better contrast/clarity and hence higher ClearType level). On the other hand, if color discrimination affects ClearType preference, there should be positive correlation between color error score and ClearType contrast but negative correlation between color error score and color attribution (lower color error → higher color sensitivity → prefer less ClearType contrast for less color fringe, but emphasize the importance of color influence).

### 5.2. Results

Table 3 presents the bivariate correlation coefficients between subject visual acuity and color discrimination with ClearType preference scores and attributed reasons. As expected, visual acuity was positively related to subjects' attribution of the 3 factors (color, contrast, and clarity) for both 10- and 12-pt fonts, but only 2 correlations (clarity at 10-pt and color at 12-pt) reached statistical significance ($p < 0.05$). This pattern suggests that subjects with better visual acuity tend to be more sensitive to the contrast, clarity and color of the text image. For color discrimination, while negatively correlated to color attribution as expected, although only one factor (color at 12-pt font) reaching statistical significance ($p < 0.05$); however, color discrimination error was negatively associated with preference of ClearType contrast level, opposite to what was expected, though the correlation is very weak and insignificant. This pattern suggests that subjects with better color discrimination are more likely to notice the color fringe in larger fonts, but they also emphasize image clarity and contrast.

Taken together, these results show that subjects with better visual acuity tended to give higher ratings of contrast, clarity and color as reasons for their preference settings, perhaps due to their better visual resolution or

Table 3
Correlation between ClearType preference and visual acuity/color discrimination

| R (p-value) | Visual acuity | Color discrimination | Preference 10-pt | Color 10-pt | Contrast 10-pt | Clarity 10-pt | Preference 12-pt | Color 12-pt | Contrast 12-pt | Clarity 12-pt |
|---|---|---|---|---|---|---|---|---|---|---|
| Visual acuity | – | 0.257 (.170) | 0.166 (.390) | 0.168 (.383) | 0.183 (.343) | 0.457* (.013) | −0.003 (.987) | 0.42* (.021) | 0.177 (.350) | 0.319 (.086) |
| Color discrimination | | – | −0.049 (.800) | −0.282 (.138) | −0.115 (.552) | −0.209 (.276) | −0.089 (.641) | −0.457* (.011) | 0.028 (.885) | −0.099 (.604) |

* $p < 0.05$.

better observational skills. People with higher color sensitivity on the other hand, emphasize the influence of color on text image. However, the results do not provide significant strong correlation of visual acuity or color discrimination to individual preference for ClearType contrast, suggesting that these tasks may not be sensitive enough to catch the fundamental traits of individual difference on ClearType preference, although they seem to be on the right track in pointing out the direction. Further investigation is needed to improve better understand about this issue to enhance better use of the sub-pixel rendering technology.

## 6. Experiment 4: color anomaly in central and peripheral vision

The results of Experiment 2 showed that perceived color was the main reason for selecting against higher ClearType levels, especially for 12-pt font. The aim of Experiment 4 was to determine if the perceived color was more bothersome in the center or periphery of the visual field. This was investigated because some subjects reported that the perceived color was more prominent when peripheral to fixation. It is plausible because the distribution of cones changes across the retina, with most color-sensitive cones concentrated in the fovea centralis and the light-sensitive rods are absent there but dense elsewhere. Traditionally color vision and the highest visual acuity in the fovea have been attributed to the measured density curves for the rods and cones on the retina, therefore it is possible that color fringe to be more serious in the central visual field. On the other hand, it has been found that peripheral stimuli are perceived with more chromatic aberration (i.e., unequal refraction of light of different wavelengths) than central stimuli, therefore it is possible that color fringe may be more serious in periphery than in fovea. If the source of color anomaly sensation can be located, further technical adjustments can be made to reduce the perceived color fringe.

### 6.1. Methods

Subject's subjective color perception of the 5 level ClearType contrast was measured in a dual-task condition. Text of various ClearType contrast was presented to subjects in 10-pt Verdana font either at the central fovea or at periphery, with viewing distance fixed at 60 cm. In the central condition, a three-line passage of text was presented in the center of the display. In the peripheral condition, a full page of text was presented except for the central three lines that were replaced with empty space. Subjects were asked to respond (with Y or N key) whether they saw color in the text. A secondary task was used to maintain subject's fixation at the central fovea. Prior to each text presentation, subjects fixated at a fixation dot in the middle of the screen. The central or peripheral text was presented for 200 ms to prevent an eye movement in response to the stimulus, during which time the fixation dot was changed to an uppercase letter C with its gap rotated to one of the four primary positions (up, down, right, or left). Subjects were requested to identify the orientation of the gap in order to ensure central fixation in addition to their response to color perception.

The central and peripheral conditions were each presented twice for each of the five ClearType levels (0–4) using Latin-Square ordering. For the first set of presentations the subjects were "naive" – that is, they were not shown the color effect to which they were responding. After the first set of presentations, a page of text with the right half presented at ClearType level 4 and the left half at level 0 was shown to the subject to point out that color effect in level 4 to which they were suppose to respond. After the demonstration, a second set of "informed" measurements were made with presentations for the 5 levels of ClearType text at central (fovea) and peripheral region at a different Latin-square order.

### 6.2. Results

The results for central and peripheral presentations are shown in Fig. 6A and B, respectively. Post-hoc pairwise comparisons determined there was no significant difference in the frequency of color perceiving between central and peripherally viewed text.

The color was more frequently perceived at ClearType levels 3 and 4 than at levels 0–2 ($p < 0.0001$), and more frequently at level 4 than at level 3 ($p < 0.0001$). For central viewing (but not for peripheral viewing), the color presence judgments were statistically more precise for the informed measure than the naïve measure ($p = 0.01$), i.e., subjects reported seeing color more often in levels 3 and 4 and than in levels 0–2 after the color fringe effect at level 4 was dem-



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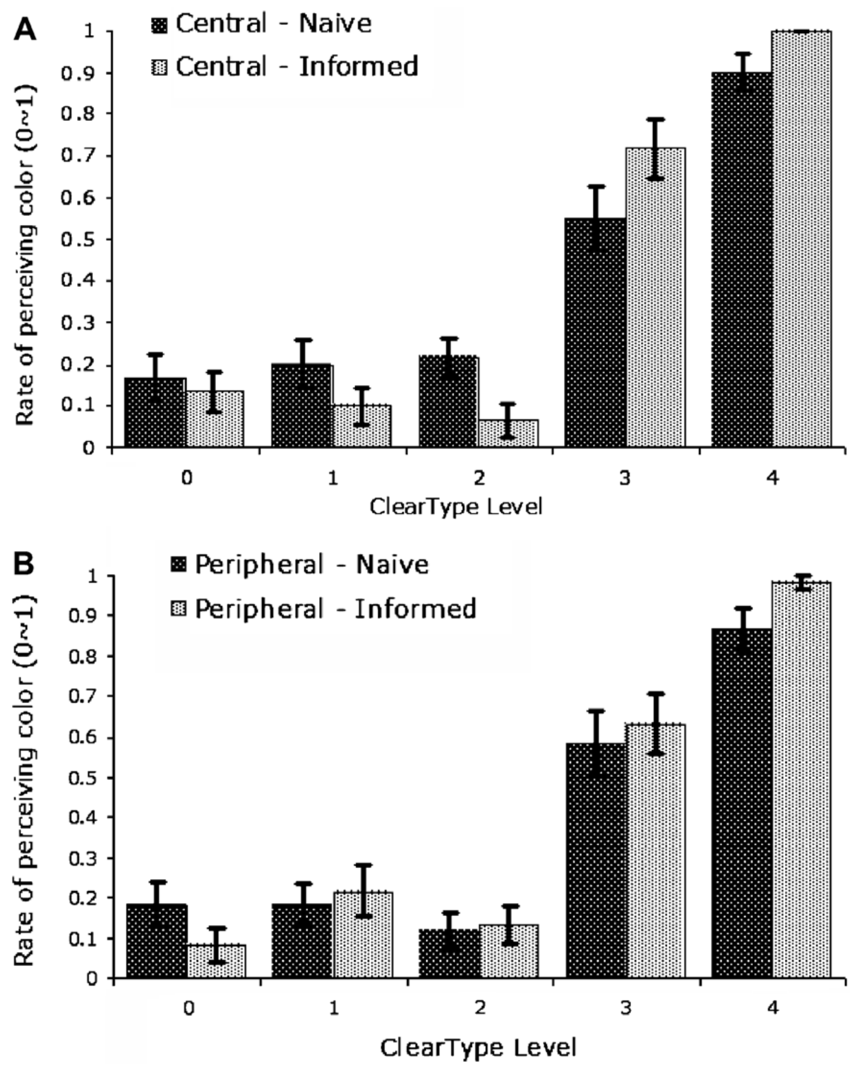


Fig. 6. Mean rating (SEM bars) of perceived color (“yes” = 1, “no” = 0) in the central viewing condition (A) and the peripheral condition (B) as function of ClearType level. Data are separated into ratings before (naïve) and after (informed) “color” in ClearType level 4 was demonstrated.

onstrated. The results do not support the argument of color sensitivity across visual field; instead, color perception was strong and robust for higher level ClearType contrast text in both fovea and periphery, suggesting that color fringing is so salient even with brief presentation and accompanied with attention-competing task.

## 7. Experiment 5: ClearType effect on reading speed and visual discomfort

### *7.1. Methods*

Experiment 5 was designed to investigate the effect of ClearType level upon reading speed and post-reading self-rating visual fatigue and discomfort symptoms.

Subjects were seated comfortable and asked to read silently. Five short passages selected from the writings of John Grisham were used as reading material. Each contained about 2500 words, presented in 10-pt Verdana font, rendered with one of the five ClearType levels (0–4) on a LCD monitor at a viewing distance of 55 cm. All subjects experienced the 5 ClearType settings at a Latin Square order to control the order effect of the ClearType condition and text difficulty.

Each passage took about 10–15 min to read, depending on individual reading speed. To normalize subject attention, 5 comprehension questions pertaining to the text were asked after reading each passage. Then subjects were asked to rate each of the following discomfort symptoms during their reading: eyestrain or fatigue, blurred vision, neck or back pain, dry or irritated eyes, and headache. Subjects marked a vertical line on a 100 mm scale (quartile locations were labeled “none”, “mild”, “modest”, “objectionable” and “severe”) to indicate the perceived magnitude of each symptom and the rating was recorded as a value between 0 and 100. A short break of about 2–3 minutes was given before reading the next passage.

Reading speed with different ClearType levels was tested with repeated measures ANOVA. Because of the large number of zeros in the symptom ratings, a non-parametric repeated measures Friedman test was used to evaluate the symptom measures. In addition, because the standard deviations of the symptom scores generally increased in proportion to the magnitude of the mean symptom score, data were transformed to log scale for statistical analysis. Post-hoc analyses were evaluated with unadjusted Wilcoxon matched-pairs tests.

### 7.2. Results

The results of reading speed with different ClearType levels are presented in Fig. 7. No statistically significant difference on reading speed was observed between conditions. Fig. 8 shows the mean symptom ratings for each ClearType level. There was a significant effect of ClearType level on eyestrain ($p = 0.014$). Post-hoc analyses revealed greater eyestrain at ClearType level 4 than levels 0, 1 and 2 ($p = 0.003$, $p = 0.02$, $p = 0.04$, respectively). There was also a trend between the degree of blur and ClearType contrast level, but the difference was not significant. Overall, the results indicate no ClearType advantage in reading speed and higher ClearType contrast seems to induce more reading discomfort. However, the testing period lasted for only 10–15 min; subjects may respond based on their first impression for the shock of color fringe in highest ClearType contrast. Future study can examine the effect with longer reading time.

## 8. Discussion

The primary advantage of ClearType over grayscale as measured in these experiments is that subjects prefer the appearance of the text, even though functional improvements were not identified. In the five experiments presented

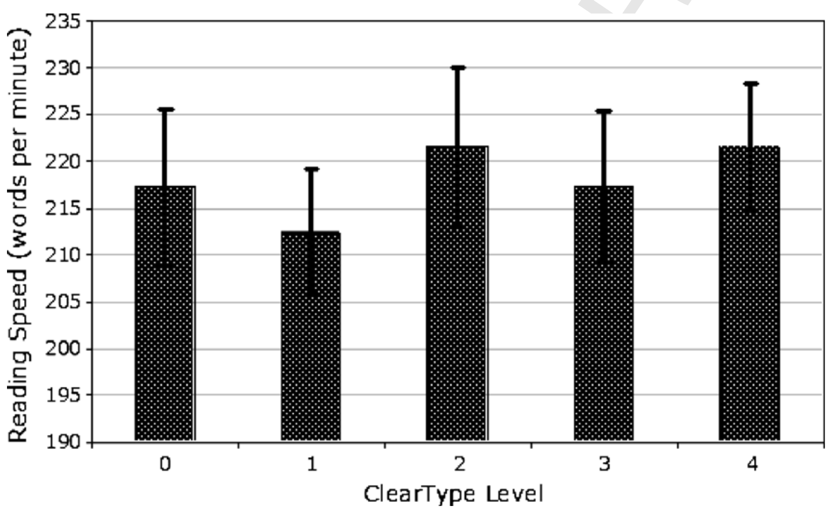


Fig. 7. Mean reading speed for each ClearType level.

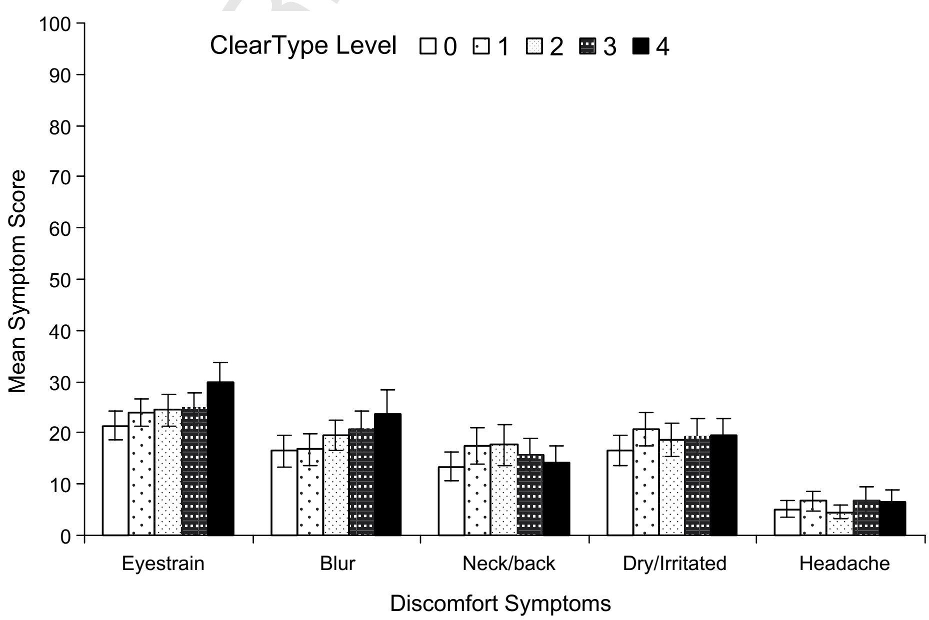


Fig. 8. Mean symptom ratings for each of five categories of symptoms after reading text displayed at each of the five ClearType levels.

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here, we compared the effects of ClearType sub-pixel rendering and standard anti-aliasing (grayscale) in a variety ways. Our goal is to address the improvement of ClearType rendering on onscreen reading both in terms of performance and readers' subjective reading comfort. We further the level of their preference to ClearType contrast and the reason for their choice and attitude (preference or aversion).

In experiment 1 we find that ClearType did not lead to better text legibility with all different levels of ClearType contrast, when compared to standard anti-aliasing (grayscale), which is different from previous findings [16]. A special note here is that, the grayscale text used in the current study is highly legible, probably more than traditional grayscale fonts, as it was created in MS Reader using the same methods that ClearType fonts are created, with all the benefits of hinting and better letter spacing, etc. This may be the reason to explain the inconsistency between the current study and Gugerty et al.'s [16]. In addition, there is no ClearType advantage in regular reading, as found in Gugerty [16] but different from Dillon et al. [18].

In Experiment 2 we presented two levels of ClearType contrast text side by side and found that subjects preferred ClearType level 1 for 10-pt font and ClearType level 2 for 12-pt font, with higher acceptance rate for ClearType level 3 at 12-pt font than at 10-pt font. The higher preferred contrast level for a larger font type is likely related to the greater number of pixels allocated to each character in a larger font. The reasons for preferring lower-level ClearType are improved perceived contrast and clarity, and the reason for aversion for higher-level ClearType is the perceived color. Anecdotally the perceived color is low in saturation and perceived in the white spaces between characters. The color is prevalent, perceived both in central and peripheral vision (Experiment 4). This result clearly indicates the need in balancing the text clarity and color anomaly, which is the heart of ClearType technology. Still, the finding that more than half subjects preferred lower-level ClearType contrast over "perceptually well-tuned" grayscale text suggested that ClearType does improve text readability, even though there is clearly individual preference in terms of the level of ClearType contrast.

The results indicate that there was variance across subjects regarding the preferred level of CT. In an attempt to understand why some subjects prefer higher or lower ClearType levels, we tested each subject's visual acuity and color discrimination ability. While the results suggest better visual acuity leads to emphasis for higher image clarity and contrast, and better color discrimination demands less color disturbance, these measures of individual visual abilities did not directly relate to preference for ClearType as hypothesized. One possibility is that the measures are not sensitive enough; alternatively, it could be that human responses to ClearType contrast are related to fundamental properties of human visual perception rather than individual sensitivity to color discrimination or visual acuity.

Finally, Experiment 5 shows that ClearType also did not improve reading speed nor did it reduce symptoms. The reading trials were only 10–15 min, hence the results can only apply to short-term reading. It is possible that effects could be measured with longer reading trials. However, the lack of improvement in reading speed and comfort is consistent with the lack of improvement in threshold legibility. It is also possible that the lack of improvement in legibility or reading performance is related to the font type and the compared grayscale text selected for this study. Verdana has been shown to be the most legible of those tested in a previous study [1]. It is possible that any functional benefits of ClearType were masked by the high legibility of Verdana, and that they might express more with a less legible font type. In addition, the grayscale text used as the control for comparison is highly perceptually tuned. In comparison to traditional grayscale text, text created in MS Reader seems more legible and easy to read overall, which may conceal the intrinsic worth of ClearType rendering. On the other hand, it also points out the actually benefit of ClearType technology: in addition to increased horizontal resolution and color balancing around strokes, ClearType also provides better hinting and kerning. Those minor changes in the format may be strong enough to explain the missing ClearType advantage that was observed in other studies but not in the current one.

In summary, we found that subjects preferred low to moderate levels of ClearType contrast because of improved perceived clarity and contrast compared to grayscale text and less color anomaly compared to higher levels of ClearType contrast; however no functional improvements were measured, when compared to perceptually-tuned Grayscale text.

## Acknowledgement

This research was funded by the Microsoft Corporation, Advanced Reading Technologies Group.

## References

[1] J.E. Sheedy, M. Subbaram, A. Zimmerman, J.R. Hayes, Text legibility and the letter superiority effect, Human Factors 47 (4) (2006) 797–815.
[2] A.C. Naiman, W. Makous, Undetected gray strips displace perceived edges nonlinearly, Journal of the Optical Society of America, A. Optics and Image Science 10 (5) (1993) 794–803.
[3] J.E. Sheedy, M. McCarthy, Reading performance and visual comfort with scale to grey compared with back-and-white scanned print, Displays 15 (1) (1994) 27–30.
[4] K. O'Regan, N. Bismuth, R.D. Hersch, A. Pappas, Legibility of perceptually-tuned grayscale fonts, in: P. Delogne, IEEE International Conference Image Processing, 1996, Proceedings ICIP-96, vol. 1, 1996, pp. 537–540.
[5] S. Gibson, Sub-pixel font rendering technology: how it works. http://grc.com/ctwhat.htm, last edited on October 06, 2003, Retrieved on January 28, 2005.
[6] R.I. Feigenblatt, Full-color imaging on amplitude-quantized color mosaic displays, Society of Photo-Optical Instrumentation Engineers: Digital Image Processing Applications 1075 (1989) 199–205.



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[7] R.I. Feigenblatt, Optimal filtering for patterned displays, IEEE Signal Processing Letters 7 (7) (2000) 179–181.
[8] Microsoft Corporation, Microsoft Research Announces Screen Display Breakthrough At COMDEX/Fall '98, http://www.microsoft.com/typography/cleartype/cleartypepr.htm (retrieved on 28.01.05).
[9] B. Hill, The Magic of Reading, http://www.poynterextra.org/msfonts/osprey.doc (retrieved on 12.02.07).
[10] ISO. Optics and optical instruments, Visual Acuity Testing – Correlation of Optotypes, American National Standards Institute, NY, 1994.
[11] C. Betrisey, J.F. Blinn, B. Dresevic, B. Hill, G. Hitchcock, B. Keely, D.P. Mitchell, J.C. Platt, T. Whitted, Displaced filtering for patterned displays, Society for Information Display Symposium Digest 31 (2000) 296.
[12] J. Platt, Optimal filtering for patterned displays, IEEE Signal Processing Letters 7 (2000) 179–180.
[13] R.A. Tyrrell, T.B. Pasquale, T. Aten, E.L. Francis, Empirical evaluation of user responses to reading text rendered using ClearType technologies, Society for Information Display Symposium Digest 32 (2001) 1205–1207.
[14] T. Aten, L. Gugerty, R.A. Tyrrell, Legibility of words rendered using ClearType, in: Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting, 2002, pp. 1684–1687.
[15] K.A. Edmonds, A. Stephenson, L.J. Gugerty, R.A. Tyrrell, ClearType increases users' performance on a sentence comprehension task, in: Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, 2003.
[16] L. Gugerty, R.A. Tyrrell, T.R. Aten, K.A. Edmonds, The effects of subpixel addressing on users' performance and preferences during reading-related tasks, ACM Transactions on Applied Perceptions 1 (2004) 81–101.
[17] A. Dillon, L. Kleinman, R. Bias, G. Choi, D. Turnbull, Reading and searching electronic documents: an experimental study of regular and enhanced screen displays, in: Proceeding of American Society for Information Science and Technology: Information Today, 2004, pp. 267–273.
[18] A. Dillon, L. Kleinman, G. Choi, R. Bias, Visual search and reading tasks using ClearType and regular displays: two experiments, in: Proceedings Conference on Human Factors in Computing Systems, Montreal, Quebec, Canada, 2006, pp. 503–511.
[19] J.E. Sheedy, I.L. Bailey, Using visual acuity to measure display legibility, Society for Information Display International Symposium Digest of Technical Papers, 1994, pp. 25.
[20] ISO, Ophthalmic optics – visual acuity testing – standard optotype and its presentation, International Standards Organization, American National Standards Institute, NY, 1994.
[21] ISO, Optics and Optical Instruments, Visual Acuity Testing - Correlation of Optotypes, American National Standards Institute, 1994.
[22] Y.-C. Tai, J.E. Sheedy, J.R. Hayes, Does the size matter? Threshold vs. suprathreshold legibility, in preparation. Q1