Effect of Lateral Chromatic Aberration for Chart Reading in Information Visualization on Display Devices

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ABSTRACT
In this paper, we explain the effect of lateral chromatic aberration (LCA) when reading information displayed on the screen and how it leads to misinterpretation of charts and values represented. Although the effect can be observed from natural scenes, we focus on LCA on modern display devices. We inform the readers of the significance of issues to those using corrective lenses, especially the high diopter eyeglasses. First, we explain the basics of LCA. Then, we present a user study to observe the effect on users' judgment when reading charts on display devices. We also introduce a prototype software-based correction method with promising results. Lastly, we suggest guidelines for information visualization designers to avoid such issues.

Categories and Subject Descriptors
H.5.3. Information interfaces and presentation (e.g., HCI): Evaluation/methodology

General Terms
Measurement, Experimentation

Keywords
Chromatic Aberration, Color Display, Information Visualization

1. INTRODUCTION
Lateral chromatic aberration (LCA) is a phenomenon that can cause image distortions when viewed through lenses. Since different colors of light refract to the different angles upon traveling through materials with refractive indices [9] (Figure 1), the resulting images may appear to be distorted. Since more and more people suffer from myopia or astigmatism, the usage of corrective lenses increases, making more people vulnerable to this type of visual distortion. In the past, it has been known that people make errors in judging sizes for the objects represented in different colors. Yoo et al. performed an experiment to test if color perception affects viewers' judgment of size of each bar in bar-charts on an LCD display [14]. They found yellow appears to be the shortest. However, some other experiment showed contradicting results [5][12][14]. Although the color-size perception can be attributed to various sources, we focus on the effect of LCA.

With ever increasing usage, it is especially worth exploring the issues based on the characteristics of the displays. Many displays use three colors of light (mainly RGB), because it provides a convenient conversion process between human color vision and the color space (also known as metamerism). The usage of three lights creates a very special phenomenon where the misperception comes from aberration of three distinct lights, unlike of the nature where wide spectrum of various wavelengths of the light is present.

This paper is organized as follows. We explain LCA in detail and along with hypotheses on the effect when reading information on the screen. Then, we present a series of controlled user experiments to show how people can misjudge information due to LCA, followed by a simple, yet effective software-based correction method, which we also verify through our user study. Finally, we conclude our paper with guidelines for the designers and developers of information visualization systems for using color.

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2. LATERAL CHROMATIC ABERRATION
LCA occurs when the lens does not focus all lights with different wavelengths to the same convergent point (Figure 1). Lights with a shorter wavelength are refracted more than the ones with longer wavelength. In RGB displays (which account for most of displays currently available in the market,) Green is refracted more than Red and Blue is refracted more than Green. Thus, white light from a monitor (which is a mix of R, G, and B) shows three distinct lights when passing through a dispersive prism or eyeglasses (Figure 2). LCA becomes much more apparent as a power of a lens increases. Also, since eyes have lenses too, LCA is present without corrective lenses [4]. Although humans are able to compensate for the error [2] especially with monochromatic aberration, the ability to correct errors caused by polychromatic aberration is still limited.

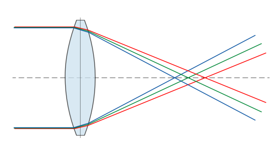

Figure 1. 'White' light from RGB displays disperse to three different lights. An image taken from Wikipedia.[1]

Figure 2. The bars on a monitor are aligned horizontally, though they appear otherwise through the eyeglasses.

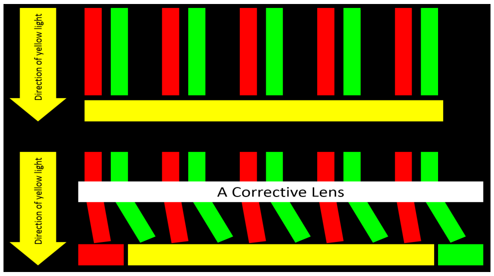

Figure 3. When yellow light travels through a corrective lens, it disperses to red and green lights. Pixels to the left might show red, while pixels to the right might show green.

Also with LCA, viewers might "see" extra categories in a color-coded chart. For example, a viewer might observe R and G at the edge of the yellow bar due to refractive angles of R and G (Figure 3) [11]. For our study, we only tested highly saturated colors against the black background. However, as refractive angle of each light is affected by wavelength, not by intensity, similar results regarding LCA would be expected for less saturated colors (Figure 4).

3. HYPOTHESES

We suspected that LCA could interfere with viewers' ability to perceive information shown on a screen accurately **(H1)**. We also suspected that it is a much more significant issue for eyeglasses wearers because combinatory index power of cornea and eyeglasses is stronger than naked eyes **(H2)**. Also, the effect of LCA will decrease as the size of stimuli increases **(H3)** according to the Weber-Fechner law; just-noticeable-difference is proportional to the magnitude of stimuli. Eyeglasses wearers do not always look straight on through the absolute center of lenses; they move their eyeballs. Also, the interval between centers of lenses can be different from wearers' eyes, or eyeglasses might slip downward during the day. Thus, the centers of lenses often do not perfectly align with the centers of pupils. Therefore, the accuracy will drop as the stimuli are farther from the center **(H4).** Finally, a software approach can be applied to reduce the effect of LCA **(H5)**.

4. EXPERIMENT

We recruited 9 participants (*Eyeglasses*) with heavy myopia with 20/200 Snellen and corrected vision of 20/25 Snellen at least. Also, we also recruited 9 more participants (*Normal*) with 20/25 Snellen with naked eyes. Upon their arrival, we checked for their visual acuity and color-blindness with pseudoisochromatic plates. The age ranged from 20 to 33 ($\bar{x}$=24.4, σ_{age}=3.5). They performed the experiment in a dark room to avoid external visual distraction [22]. A chinrest was used to keep their eyes 52 cm apart from a display. The screen was 27" with 2560 x 1440 pixels. Thus, one pixel accounted for 0.0257° visual angle.

As other research on color-perception suggests, the issues come from the combination of various sources like physiological limitations of our visual system and psychological reasoning of our perception, which makes it difficult to purely attribute the problem

Figure 4. LCA in less saturated color. A brown patch can be seen on the left-side and a blue patch on the right-side.

[26] to LCA. Throughout the study, we performed our experiment against *Eyeglasses* and *Normal* groups while keeping other compounding variables controlled. We did not vary the lens applied to each participant, because applying a different lens to an eye results in blurry edge due to changes in focal length, and it can become another source of error [4].

4.1 Alignment Task

4.1.1 Study Design

We suspected that, if LCA is involved, viewers are likely to misjudge the alignment of each square (Figure 5). A real life example of this can be judging the height of each bar in a bar-chart since each bar is often painted with different colors to show its category (Figure 7).

The subjects performed one of *Vertical* and *Horizontal* alignment conditions first, and moved onto the other. We did not mix two conditions because the task would be confusing. However, we mixed the order of RG and RB pairs and various sizes in order to minimize learning effect. All pairs were always aligned, and we showed only one out of fifteen pairs at a time on each type of stimuli shown in Figure 5. After answering a question on the alignment of each pair, the difficulty of making judgment was asked on a three-point scale (*Easy*, *Medium*, *Hard*). The significant of difficulty rating was that, the harder to make a judgment, the less obvious, and it was 'a close call.' (i.e. the effect of LCA is less noticeable.)

The practice questions included very obvious ones with significantly misaligned squares. For every 15 questions, we inserted a transition screen for a break. Because some people tend to balance their multiple-choice answers and thus answer in a way not faithful to their actual perception, we asked them to be as honest as possible as the purpose of the experiment was not to test their ability to decode information, but rather to understand perception. Since we tested twelve types of stimuli (3 sizes × 2 orientations × 2 pairs) with fifteen pairs for each, we collected 180 judgment-difficulty pairs per user and in total 3240 pairs for 18 subjects. We also measured the response time for each pair.

4.1.2 Result

In total, 2228 out of 3240 pairs were answered incorrectly. (i.e. the subjects did not choose "Perfectly aligned") **(H1)**. RB pairs showed more incorrect answers (n=1331) than RG pairs (n=897) [$\chi^2(1)$=269.417, n=3240, p<0.0001]. The subjects in the *Eyeglasses* group showed more incorrect answers (n=1187) than ones in the *Normal* group (n=1041) [$\chi^2(1)$=30.212, n=3240, p<0.0001] **(H2)**.

For *Eyeglasses*, the number of incorrect answers decreased in order of *Small* (n=431), *Medium* (n=404) and *Large* (n=352) [$\chi^2(2)$=30.492, n=1620, p<0.0001] **(H3)**. Also, pairs in the first/fifth (n=503) and the second/fourth columns (n=461) showed more incorrect answers than pairs in the third column (n=223) [$\chi^2(2)$=11.035, n=1620, p=0.0040] **(H4)**. However, pairs in the bottom row (n=428) and the middle row (n=400) showed more incorrect answers than pairs in the top row (n=359) condition [$\chi^2(2)$=22.776, n=1620, p<0.0001] **(Contrary to H4)**. While the reasons are to be verified in the future, the results are consistent with literatures on upper- and lower vision [3][10].

For *Normal* group, we did not find such patterns regarding size, and column and row locations, meaning that the group with *Eyeglasses* experienced the issue much more than *Normal* group.

Using Spearman's rank correlation test with difficulty rating and response time, we saw a significant correlation (p<0.0001). However, the coefficient was only 0.349. The difficulty was given

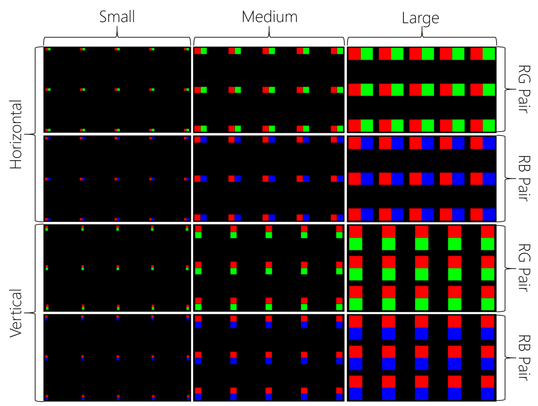

Figure 5. Left, middle, and right columns show *Small*, *Medium*, and *Large* conditions respectively. The first two and the last two rows show *Horizontal* and *Vertical* conditions respectively.

a numeric value (1 for *Easy*, 2 for *Medium*, and 3 for *Hard*) and was analyzed with a 2 (visual acuity) × 3 (column location) × 3 (row location) × 3 (size) × 2 (orientation) × 2 (color combination) Factorial ANOVA and Tukey's HSD post-hoc test.

We found a significant main effect of *row location* ($F_{2,1296}$=6.577, p=0.004), with post-hoc tests showing that the effect was driven by *Top Row* ($\bar{x}$=2.21, σ_{age}=0.82) with significantly higher difficulty rating than both *Middle Row* ($\bar{x}$=2.11, σ_{age}=0.83) and *Bottom Row* ($\bar{x}$=2.05, σ_{age}=0.85) (p=0.039 for both) **(Contrary to H4)**. Although contrary to **H4**, the result is consistent to that of accuracy.

We also found interactions: Row × Orientation ($F_{2,1296}$=13.178, p<0.001); Row × Color Combination ($F_{2,1296}$=3.480, p=0.031); Size × Color Combination ($F_{2,1296}$=4.399, p=0.012).

4.2 Number of Colors Task

4.2.1 Study Design

The general design was similar to that of the *Alignment* task. One square from Figure 6 appeared on the screen at a time where they had to answer the number of colors they saw.

4.2.2 Result

In total, 968 out of 1620 squares were answered incorrectly (i.e. the subjects did not choose "observed only one color") **(H1)**. Magenta (RB) (n=528) caused more incorrect answers than Yellow (RG) (n=440) [$\chi^2(1)$=19.428, n=1620, p<0.0001]. The subject with *Eyeglasses* (n=586) had more incorrect answers than *Normal* (n=382) [$\chi^2(1)$=105.775, n=1620, p<0.0001] **(H2)**.

For *Eyeglasses*, the first/fifth (n=248) and the second/fourth columns (n=324) had more incorrect answers than the third column (n=106) [$\chi^2(2)$=6.813, n=810, p=0.0332] **(H4)**. Also the bottom (n=217) and the middle row (n=215) had more incorrect answers than the top (n=154) [$\chi^2(2)$=47.478, n=810, p<0.0001] **(Contrary to H4)**. This is consistent with the accuracy result from *Alignment*. However, For *Normal* group, we did not find such patterns regarding size, and column and row locations.

There was significant correlation (p<0.0001) between difficulty and response time. However, the coefficient was, again, only 0.3405. One-way ANOVA revealed that *Eyeglasses* ($\bar{x}$=1.7938) showed higher difficulty rating than *Normal* ($\bar{x}$=1.5778) [F(1, 1620)=34.055, p<0.001]. Also, for *Eyeglasses*, the middle row ($\bar{x}$=1.8630) had higher difficulty rating than the bottom row ($\bar{x}$=1.6889) [F(2, 810)=3.497, p=0.031] **(H4)**.

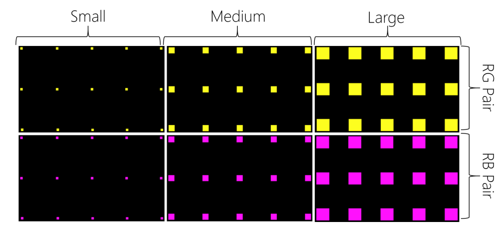

Figure 6. Left, middle, and right columns show *Small*, *Medium*, and *Large* size conditions respectively. Each row shows *Yellow* (Red+Green) and *Magenta* (Red+Blue) combo.

4.3 Corrected Alignment Task

There is no universal solution that works for everyone to lessen the effect of LCA. Long telescopes or achromatic optics would be an unviable solution for everyday use. Also, we often do not remember prescription of our eyeglasses. (And even if we do, it's never 100% accurate due to the limitation of everyday eye exam.) And since many people suffer from astigmatism, no single model is perfect. In our study, we suggest a simple control point based correction method. We borrowed the post-processing concept implemented in digital cameras and photo editing tools that spatially warps RGB channels to align them. Although a projective linear warping is not accurate description of lenses with a higher order [8], we hypothesized that a simple linear warping could lessen the effect to some meaningful extent within the visual angle of the screen in an office environment **(H5)**(Figure 7). Please note that our solution is not ultimate, but rather, is to demonstrate how warping color spaces reduce the LCA effect and help viewers perceive correctly.

We used four control points (in each corner of a screen) to measure the magnitude of aberration. We showed a pair of small RG squares horizontally aligned to each corner. To many viewers' eyes, they appeared not aligned. They moved green squares vertically to align them to the red ones with a keyboard. Each key strokes moved each stimuli only a tenth of a pixel (subpixel). This gave us the amount of green light aberration at each corner. We repeated the task for RG squares vertically aligned. We also repeated one for RB pairs. Then, we computed projective warping matrices for both G and B with respect to R. After the matrices had been acquired, we asked the participants to perform the same Alignment task again.

4.3.1 Result

Normal exhibited a shorter Euclidean distance between actual points and warped points than *Eyeglasses* for both G and B channel **(H2)**. For G, the average correction distance of *Normal* and

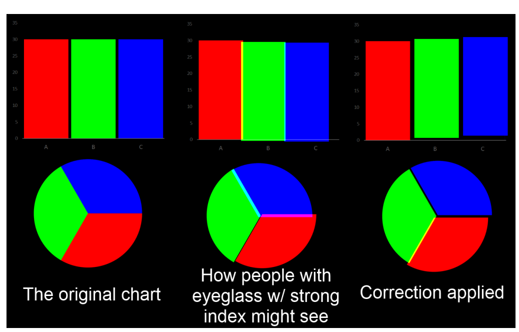

Figure 7. The effect of LCA can be reduced by artificially shifting color channels to the opposite direction (right). Artificially shifting them up-right (right) will make the image perceived normally as the original (left).

Eyeglasses were 1.5570 and 2.3802 pixels respectively [$F_{1,18}$=6.610, p=0.021]. For B, the average corrected distances of *Normal* and *Eyeglasses* were 2.9198 and 5.5112 pixels [$F_{1,18}$=11.140, p=0.004] respectively. The result matched the natural phenomenon of blue light being refracted more than green.

Number of incorrect answers for *Corrected Alignment* (n=1489) dropped compared to *Alignment* (n=2228) for both *Eyeglasses* [$F_{2,3240}$=124.356, p<0.0001] and *Normal* [$F_{2,3240}$=230.474, p<0.0001] **(H5)**. Also, *Corrected Alignment* ($\bar{x}$=2.2179) showed higher difficulty ratings than *Alignment* ($\bar{x}$=2.1228) for both *Eyeglasses* [$F_{2,3240}$=4.067, p=0.044] and *Normal* [$F_{2,3240}$=22.618, p<0.001] **(H5)**, meaning the squares appeared to be more aligned for *Corrected Alignment* than for *Alignment*. Also *Corrected Alignment* ($\bar{x}$= 1.8634) showed longer *response time* than *Alignment* ($\bar{x}$= 1.6786) [$F_{2,6480}$=51.669, p<0.001] **(H5)**.

5. DESIGN GUIDELINES

Based on the results, we present design guidelines for using colors in information visualization systems.

Colors with a large difference in wavelength should not be presented adjacent to each other. If the lights are adjacent to one another, people wearing strong refractive lenses will see colors that should not exist. Also, make the physical separation of colors more apparent if they are rendered farther away from the center of visual angle **(H4)**. For example, when a wall size display is at a close range, a large portion of the screen goes outside of normal visual angle. In this scenario, users may glance sideways. In such case, people will look through rather thicker part of lenses where the distortion becomes much more significant.

When making charts, consider using additional codings such as labeling or drawing additional gridlines. Although [14] suggested drawing gridlines to overcome color-size perception issue, it can also be applied to LCA. For example, the gridlines can help reduce perceived ambiguity when reading bar charts using multiple colors.

When possible, make stimuli as large as possible. Since the effect of LCA decreases as the size of stimuli gets larger **(H3)**, we can benefit by making them sufficiently large. Future works might reveal how large is “sufficient” for different types of stimuli.

As mentioned above, no solution is universally effective under different environments. Although we do not say LCA should always be corrected under all circumstances it is worth the attention of visualization researchers to understand the phenomenon (i.e. errors) caused by the objects we are familiar with, like eyeglasses.

6. CONCLUSION / FUTURE DIRECTION

In this paper, we looked into the issues involving LCA, and its significance in the context of information visualization. We found that LCA can lead people to misjudge information shown on displays. We proposed a simple correction method, along with its promising results. We also presented design guidelines for using colors in information visualization systems.

In the Future, we can explore further into using applying correction to real environment. If the screen is attached to head (like head-mounted displays), or the location of head can be tracked correctly, we can dynamically warp respective color spaces to counter-affect LCA. It will be ultimately like putting a virtual lens on top of our screen, which ‘cancels’ the distortion without affecting the quality of images, just like using achromatic optics. Since we have to deal with three channels, transformation can be done very fast on GPU.

We can also look into different degrees of aberration. A quantitative prediction on the amount of aberration depending on the wavelength and the power of eyeglasses will let us estimate the threshold on which viewers start to misinterpret the chart [7]. We can also consider other types of commonly discussed chromatic aberrations like axial chromatic aberration, which contributes to the possible cause of illusory depth effects [13] in order to understand the effect and provide possible solutions.

7. ACKNOWLEDGMENTS

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